Resolution Revolution:
The Future of Ultra High Definition Television

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Declaration:

I declare that the work described in this research Paper is, except where otherwise stated, entirely my own work and has not been submitted as an exercise for a degree at this or any other university.

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Abstract

High Definition Television (HDTV) has reached a period of relative maturity after a considerably long gestation period from early experiments in the 1970s through to final international agreement on HDTV standards in the mid-2000s. A number of drivers advanced the final successful widespread introduction of HDTV around the world. Many of these factors were closely related to key advances in technology, including the development of flat-panel displays which presented the possibility of larger screens than had been possible with older Cathode Ray Tube (CRT) technology. The introduction of Digital Television (DTV) standards and platforms allowed signal compression which afforded the extra bandwidth required to deliver additional channels and HDTV services.

With HDTV equipment now firmly embedded within consumers' homes throughout much of the developed world, manufacturers of televisions and display equipment are looking to the next innovations that can drive sales of equipment over the coming years. The position of front-runner for the next potential evolutionary step in mainstream television is Ultra High Definition Television (UHDTV), with the "4K" format being widely adopted by manufacturers and offered in many medium-cost televisions and projectors. Japanese broadcaster NHK is working toward the launch of an "8K" resolution UHDTV service, offering 16 times the number of pixels of HDTV, within the next five years. In addition to increased image resolution, the UHDTV formats promise faster frame rates, greater dynamic range and a wider colour gamut.

As with all prior innovations in the field of consumer audio visual equipment, the success of UHDTV will depend upon a critical mass of support from both content providers and consumers as well as equipment manufacturers. This research paper examines the challenges that UHDTV faces in the current environment and the future within the context of historical examples of both successes and failures in the field of television and home video. Opportunities for UHDTV are also identified and conclusions are drawn regarding the future of UHDTV.

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Glossary

4K/8K	UHDTV resolutions referring to approximate screen width in pixels.
Artefact	Undesirable flaw or distortion in a television image.
Aspect ratio	Ratio of screen width to screen height.
Bit depth	Number of bits making up a digital video sample.
Colourimetry	Quantization of colour.
CRT	Cathode Ray Tube.
Definition	Sharpness or resolution of a television image.
DTV	Digital Television.
Dynamic range	Range of contrast that can be encoded or displayed for a pixel.
Field	One individual image in an interlaced frame. 2 fields = 1 frame.
Field of view	The horizontal viewing angle of a screen in relation to a viewer.
Fps	Frame rate of a television image in frames per second.
Frame	One individual image of a sequence making a moving image.
HDTV	High Definition Television.
Interlaced Scan	Scan in which adjacent rows are processed separately in two passes.
ITU	International Telecommunications Union.
Lines of Resolution	Measure of the horizontal definition of an analogue television.
Lossy compression	Compression technique in which information is irrecoverably lost.
MPEG	Moving Picture Experts Group (digital video standards).
NTSC	National Televisions Systems Committee (analogue TV standards).
PAL	Phased Alternating Line (colour analogue TV standard).
Progressive Scan	Scan in which all rows are processed sequentially in a single pass.
Scan Line	Horizontal line traced across a CRT to form part on an image.
SDTV	Standard Definition Television.
SECAM	Sequential Colour with Memory (colour analogue TV standard).
SMPTE	Society of Motion Picture and Television Engineers.
Spatial resolution	The resolution of a television image in terms of pixels.
Temporal resolution	The frame or field rate of a television signal.
Time-Shifting	Recording of television broadcast for playback at a later time.
UHD-1/UHD-2	Standards for UHDTV (widely known as 4K and 8K respectively).
UHDTV	Ultra High Definition Television.

Chapter 1 - Introduction

This research paper considers the future of Ultra High Definition Television (UHDTV) which provides the next incremental step in the improvement of image quality of television over the High Definition Television (HDTV) formats that have augmented Standard Definition Television (SDTV) broadcasts in many countries. UHDTV promises an improved viewer experience over HDTV through increased spatial resolution, faster frame rates, greater dynamic range and a wider gamut of colours [2]. These improvements are built on technologies that heralded the transition from the analogue television standards of the twentieth century to the digital encoding and delivery of television signals and the move to HDTV that occurred over the last twenty years. Two image resolutions, commonly referred to as 4K and 8K, are proposed for UHDTV providing a 4 and 16 fold increase in pixels respectively over HDTV resolutions [3]. The availability of 4K resolution television displays and some material through internet and broadcast platforms in some regions means that UHD has arrived. However the format is still in its infancy as standards are yet to be finalised.

The subject of this research arose from a visit to an electrical retailer where a number of 4K resolution televisions were on display. My immediate thought as a consumer familiar with HDTV technology was that such televisions would give little or no discernible benefit over a HDTV in most domestic environments. My opinion of the limited benefits of UHDTV was intensified by my belief that the gap in visual quality between SDTV and HDTV is artificially widened by some broadcasters as a result of the meagre bandwidth allocated to SDTV channels. This led me to the question:

What does the future hold for UHDTV, ubiquity or paucity?

Considered evaluation of this question requires identification of the challenges that UHDTV faces in the consumer market and the opportunities that it can leverage to be successful. The approach taken to identify these challenges and opportunities includes examination of UHDTVs relationship with HDTV and SDTV. Television has evolved enormously in the nine decades since the first broadcast services were established. However many of the choices made in the development of UHDTV standards are impacted fundamentally by decisions made during those nine decades. Analysis of the history of television also provides the opportunity to identify previous events that might indicate similar challenges or opportunities.

Key developments during this history from the beginnings of analogue television through to televisions' relationship with the internet are described in Chapter 2. This history details previous revolutions and challenges that have been faced during the development of television. Chapter 2 also lays the groundwork for many of the technical considerations in the development of HDTV and UHDTV which are examined in Chapter 3. Chapter 4 presents the challenges and opportunities that are identified for the future of UHDTV as a consumer format on the basis of analysis of the previous two chapters. Chapter 5 draws conclusions from the research and provides an answer to the question stated above.

1.1 State of the Art

There is no currently published academic research into the factors that will influence the success or otherwise of UHDTV as a mass consumer product or what impact UHD is likely to have on television as a viewing medium. Discourse on the future of UHDTV within the home and its place within the wider world of television and related technologies remains within the purview of industry commentators and trade publications.

Extensive work has been undertaken in the development of UHDTV standards by organisations such as the Society of Motion Picture and Television Engineers (SMPTE) and the International Telecommunications Union (ITU), as well as broadcasters including the Japan Broadcasting Corporation (NHK) [4]. The field of UHDTV is currently an area of significant research. This research mainly concentrates on technical aspects of UHDTV, such as optimum parameters for UHDTV standards and methods for generating, processing, encoding, delivering and displaying UHDTV signals. Inevitably human factors are studied in addition to technical considerations in much of the research into UHDTV [5, 6].

1.2 Exclusions

Sound forms a key part of the standards adopted for UHDTV and builds on improvements added by HDTV and throughout the analogue age. However for the purpose of this research a decision has been taken to concentrate on the visual elements of television only.

UHDTV technology has the potential for many uses in large screen presentation in theatre, gallery, museum and applications. This research does not consider UHDTV beyond its potential use in a domestic environment.

1.3 Document Overview

Chapter 2 examines the history of television and related technologies from its inception through to the transition from analogue to digital delivery of television programming. This provides a basis to compare the medium as it existed through the twentieth century to the HDTV formats that are established today and the UHDTV formats and services that are under development.

Chapter 3 takes a detailed look at HDTV and UHDTV. The relationship of these digital television formats to earlier analogue systems is explored together with a number of fundamental concepts that underpin the technology.

Chapter 4 identifies challenges that could impact UHDTV's widespread adoption by society. The opportunities that are available to help realise this goal are also discussed.

Chapter 5 presents conclusions from the research conducted.

Chapter 2 - A History of Television Technology

In the time since its theoretical beginnings television transformed from a novelty to a medium that pervades the lives of many people in the developed world. Television has advanced technically as well as in terms of content and use. This chapter explores the history of television and its development toward the myriad of methods that now exist for the delivery and display of moving images to viewers inside and outside of the home.

2.1 The First Fifty Years

Early ideas for sending visual images electrically began to surface following the discovery of the photosensitivity of selenium in 1873. The exposure of selenium to light significantly increases the element's electrical conductivity. The discovery of this property, allied with a number of earlier developments such as the copying telegraph and the telephone, together with discoveries related to light and electromagnetism, prompted no less than ten distinct proposals relating to the transmission of images over the years 1878 to 1884. Over the remainder of the nineteenth century a variety of further ideas were put forward, from suggestions for individual elements through to complete systems, by individuals in eleven different countries [7].

The early proposals suggested means for both monochrome and colour image transmission over wired circuits as well as wirelessly. In all cases, image scanning was suggested by mechanical means similar to that implemented by the copying telegraph. The first recorded use of the word "télévision" appears in the title of a report, in French, for the International Electricity Congress in 1900 by Russian scientist Constantin Perskyi [8, 9]. For the most part, experiments relating to these early ideas were limited by the lack of supporting technology. It was the mid-1920s before many of the ideas and proposals of the previous fifty years could be fully explored and used as the basis for working systems [10].

2.2 Early Television Implementations

During the 1920s John Logie Baird and Charles Francis Jenkins were working in the United Kingdom (UK) and the United States of America (USA) respectively to implement mechanical systems based on some of the early proposals outlined in section 2.1. Both succeeded in transmitting small silhouette images as early as 1925. The images were made up of a number of lines that were scanned one at a time by the camera equipment and reproduced on the receiving equipment. The initial systems had line counts as low as 16 but these numbers increased as refinements were made [10].

Figure 1: John Logie Baird with the transmitting portion of the original experimental Baird television apparatus, September 1926 [1]

Figure 2: The oldest known photograph of a televised image – produced by Baird's equipment (circa 1926) [1]

Over the years that followed Baird, Jenkins and a number of others began transmitting experimental television signals. By the early 1930s television receivers and components were available to consumers in the UK and the USA. However the systems were of limited picture quality and television was little more than a curiosity. This changed with the development of camera tubes that could scan images electronically. In 1936 the British Broadcasting Corporation (BBC) began simultaneously trialling both Baird's mechanical system and an electronic "high definition" system featuring cameras developed by Electric & Musical Industries Ltd (EMI) and transmitters developed by the Marconi Company. Baird's system used 240 scan lines at 25 frames per second (fps) while the EMI/Marconi system was based on 405 scan lines at 25 fps interlaced. A frame rate of 25 fps, was adequate for human persistence of vision to perceive the sequence of still images as moving but the human eye would still detect flicker at this rate. Interlacing reduces the perception of flicker by dividing each frame into two fields as can be seen in Figure 3. The first field scans odd lines 1,3,5,7 etc. The second scans even lines 2,4,6,8 etc. While each scan line still flickers once per frame, the flicker of the adjoining scan lines is displaced by half of the frame rate resulting in an overall effect in which the flicker can no longer be perceived [11]. The alternate method of scanning each line sequentially in a single pass is called progressive scan. Aside from its inferior image resolution, Baird's mechanical system used cameras that were by necessity large and unwieldy in comparison to the EMI cameras. The heavy promotion of the Baird system was not enough to overcome these disadvantages and the 405-line system was adopted as the standard for British television in 1937.

Figure 3: Interlaced scanning method

In the USA a number of incompatible services had begun broadcasting but the need for a single standard led to the establishment of the National Television Systems Committee (NTSC). By March 1941 agreement had been reached between the NTSC and the television industry for a set of standards covering all technical aspects of television broadcasting in monochrome. These standards were based on 525 scan lines at 30 fps interlaced [10, 12]. The choice of frame rates resulted from effects between the alternating current power supply and Cathode Ray Tubes (CRTs) that were manifested as patterns on the display. If the frame rate was not a multiple or a factor of the frequency of the power supply these effects moved across the image and became far more pronounced. Using a field rate that matched the electrical frequency of 50Hz in the UK and 60Hz in the USA averted this concern as the patterns when stationary were imperceptible [11].

Despite the interruption of World War II, development of television services continued in other countries and by 1950 broadcasters in much of Europe had settled on systems that were based on 625 scan lines at a rate of 25 fps interlaced [10].

2.3 Colour

Despite some early successful colour television experiments the standards adopted throughout the world prior to 1950 were monochrome. In the early 1950s interest in colour television in the USA began to increase. However the success of television presented a challenge given the large number of viewers with monochrome television sets. A new NTSC standard in 1953 provided a solution that allowed viewers with monochrome NTSC receivers to view colour broadcasts albeit in black and white. This backward compatibility was achieved by the use of a luminance-chrominance system in which the colour image was split into two components. The luminance component, a register of brightness, was compatible with the original monochrome signal. The chrominance component carried the colour information. Legacy black and white television sets ignored the additional chrominance sub-carrier in the signal and displayed just the luminance component. However there was potential for interference between the new chrominance sub-carrier and the existing audio sub-carrier. The workaround was to reduce the frame rate by 0.1% to 29.97 fps, which was well within the tolerances for legacy receiving equipment [13, 14].

The NTSC approach was adapted in Europe to produce the Phase Alternating Line (PAL) and Sequential Colour with Memory (SECAM) standards. By the mid-1970s most countries were using 525-line NTSC or 625-line PAL/SECAM systems [10].

2.4 Delivery of Television in the Analogue Era

The first implementations of television broadcasting were via radio waves. The bandwidth required for the analogue signals was directly related to the information that needed to be carried so higher definition pictures and higher frame rates required more bandwidth. Limitations in the available radio frequency spectrum consequently enforced limits on the number of channels that could be supported. Broadcasting via radio could provide viewers with television pictures over wide areas without the need for physical connectivity. However some areas suffered from poor reception due to terrain or distance from transmitters. Community Antenna Television (CATV), later known as cable television, was introduced as a solution to these problems. Signals acquired from high quality antennae were redistributed to consumers via wired connections. The additional bandwidth available in these cables allowed the broadcast of additional channels. This was something that cable companies were able to exploit by providing additional pay-television services for sporting events and movies. The space-age brought about the possibility of broadcasting television signals via satellite. By the mid-1960s it was possible for broadcasters to obtain live television from almost anywhere in the world. Prior to this film recordings had to be made and then physically transported to the broadcast location for replay into television equipment. Satellite technology also presented the opportunity of delivering television broadcasts directly to consumers [10].

The analogue nature of television presented problems from a transmission standpoint. The bandwidth requirement was considerable and consequently there was a limit in the number of channels that a broadcast spectrum could accommodate. Also, analogue signals were susceptible to interference resulting in degraded pictures with problems such as ghosting or snow (Figure 4) being common. Nonetheless analogue television remained centre stage from a broadcast perspective throughout the twentieth century broadly based on the standards and transmission technologies that had been pioneered through to the 1970s.

Figure 4: Simulated images showing ghosting and snow in analogue television caused by interference and weak signal

2.5 Television Recording

Television as conceived and developed in its early days was a live medium. The ability to store and replay television was recognised as being desirable by broadcasters but presented significant challenges. The development of a device called the kinescope permitted the filming of television images through a film camera pointed at a monitor. Once developed the film could be retransmitted by effectively pointing a television camera at a projection. This technique permitted time-lapse of television programming, editing and also distribution of programming between different territories.

The development of Video Tape Recorders (VTRs) such as Ampex's 2 inch Quadruplex Videotape in 1956 proved to be a major boon to the television industry. Unlike with film, which had to be developed prior to playback, recordings could now be played back in the time it took to rewind tape. Editing was possible through splicing of tapes and the expensive media could also be wiped and re-used. Later systems into the 1960s increased capacity while providing more versatile features such as still frames and slow motion. In addition to tape a number of magnetic disc based systems for recording were built around the 1960s. Early systems had small capacities of tens of seconds, but would allow near instantaneous retrieval of any frame and fast a slow motion playback and rewind. This made these systems particularly suitable for providing slow motion replays in sports broadcasting [15-17].

2.6 Digital Television

> *"The great advantage of handling television signals digitally is that digital quantities are capable of being sent, received, switched, stored, recorded and delayed virtually without distortion. Whatever bad effects accrue from conversion to and from the digital mode need accrue only once. Whatever ills can befall a digital signal, short of total loss, they can be made invisible and they do not accumulate."*
>
> Busby [18]

During the 1970s and 1980s it was not felt that there was a huge improvement to be gained in transmitting television digitally to the consumer. However, digital recording and distribution through internal networks offered many advantages to broadcasters. Key amongst these was eliminating the loss of quality in multi-generational video recordings. There was also the consideration of bringing some unification to standards in order to simplify program exchange between different territories [19]. Consequently much of the work carried out at this time was aimed at producing formats for professional video recording and distribution. The move to digital required consideration of how the images should be sampled to produce a stream of digital bits and what sampling frequencies and number of bits should be recorded for each sample. Bit rates became the digital equivalent of analogue bandwidth. Initial aims were to produce video that would show no degradation in quality over the existing analogue systems. Experimental digital video tape recording equipment with a data rate of 230 Mbit/s was demonstrated in 1981 showing no noticeable degradation on a 23rd generation copy [20].

By the mid-1990s digital video was widely used within television studios. However data rates remained well beyond a level that could be used for transmission purposes [21]. The key to reducing data rates to levels suitable for broadcast lay in forms of image compression initially developed by the computer industry. Still image formats such as that developed by the Joint Photographic Experts Group (JPEG) had demonstrated that significant compression could be achieved without severely impacting visual quality. The Moving Picture Experts Group (MPEG) was established in 1988 by the International Standards Organisation (ISO) and the International Electro Technical Commission (IEC) as a working group to define standards for audio and video compression and transmission. The MPEG-1 specification in 1992 was followed two-years later by MPEG-2 which employs two key techniques to compress digital video:

- Spatial compression involves looking for pixels in an individual frame that are the same as or similar to others in that frame. A similar method of compression is used by JPEG for still images.

- Temporal compression takes advantage of the similarities from one frame to the next by recording only the differences between them.

Figure 5 shows a scene that has the opportunity for significant compression through these means. The image contains many areas with pixels of similar colour and contrast, particularly in the sky and sand. As a video of horses galloping across the beach, large sections of the images composing each frame will not change from one frame to the next.

Figure 5: Example of a scene that offers opportunity for significant MPEG compression [22]

The compression techniques employed by the MPEG specification are lossy, meaning that data is discarded during the compression process. The level of data that is lost depends primarily upon the bit rate allocated to the video and complexity of the video being compressed. Noticeable distortion to the video through this loss of data is referred to as a compression artefact. MPEG-2 provided the solution to compressing 525-line and 625-line digital video to a level that could comfortably fit inside the existing broadcast spectrum with little perceived loss in quality [23, 24].

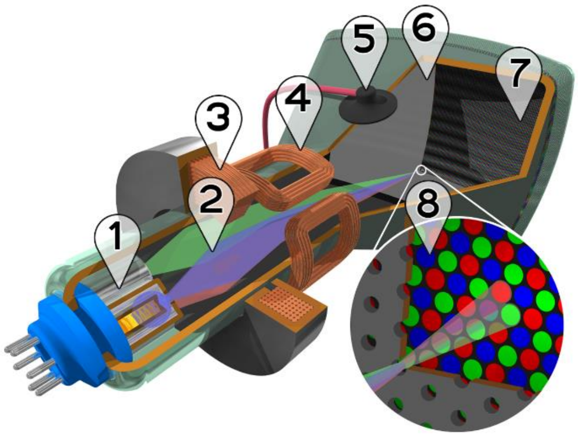
Development of Digital Television (DTV) took place separately under the supervision of the Advanced Television Systems Committee (ATSC) in the USA, the Digital Video Broadcasting Project (DVB) in Europe as well as organisations based in Japan, China and South Korea. The result is a number of different but similar standards for broadcasting DTV over various mediums including terrestrial, satellite and cable. These standards permit the bit streams for multiple digital channels to be multiplexed together into a single transport stream for broadcast. This allows a number of channels to share the bandwidth of a single frequency channel with bandwidth being dynamically allocated to different channels depending upon their needs. For broadcasting purposes digital encoding and multiplexing must take place in real time. This places challenges in terms of the capacity and speed of hardware and the efficiency of the algorithms that are used [25-27].

Digital broadcast was clearly incompatible with the analogue receivers built in to existing television sets. However, the lower bandwidth requirements of the digital channels allowed digital and analogue services to be run concurrently, giving viewers time to upgrade equipment. "Set top" boxes that could decode the digital signal and provide output in analogue form to older equipment, offered a cheaper alternative to upgrading a television set. DTV services first became available in the USA and UK in 1998, followed by other countries in the following years. Many European countries had ceased analogue transmission by the end of 2013, although some cable television providers in these countries still deliver analogue signals. Most countries that are still providing an analogue signal plan to discontinue these services by 2021.

2.7 Display Technology

Early mechanical experiments and systems used a variety of apparatus to capture and display moving images. However the move to electronic scanning and rendering of television pictures put the CRT at the heart of television display until the end of the twentieth century. The CRT was rooted in the development of the Braun tube in the 1890s but its use in television was first proposed by Boris Rosing in 1907. The development of CRTs for the purpose of commercial television was primarily carried out by Dr Vladimir Zworykin for both display and scanning purposes [28]. Early CRT television sets had small screens usually of 5 to 7 inches which were generally round and were housed in large cabinets to accommodate the valves that they required to operate. Over time, technological improvements led to larger screens and smaller cabinets [12, 29]. Early television screen sizes were measured as the diameter of the CRT. As CRTs became less rounded the convention of measuring diagonally from opposite corners of the screen was adopted. This convention persists in screen measurements for all televisions today.

The development of colour CRTs in the 1950s paved the way for the introduction of colour television [30]. This technology improved considerably in quality and reliability throughout the remainder of the twentieth century.



1. Electron guns
2. Electron beams
3. Focusing coils
4. Deflection coils
5. Anode connection
6. Colour mask
7. Phosphor layer
8. Close-up of the phosphors

Figure 6: Illustration showing the interior of a colour Cathode Ray Tube [31]

Direct-view CRTs were by far the most popular television display equipment throughout the twentieth century and by the last decade of the 1990s sets were available in sizes ranging from a few inches up to around 40 inches. Much had been done to overcome the manufacturing and technological challenges that limited the size of early CRTs. CRT screens had become larger, less rounded at the sides and flatter across their face. However the volume and thickness of glass required in large sets made them extremely heavy. A practical limit in television size had been reached.

In the 1990s, rear-projection televisions using smaller CRTs to overcome the constraints on depth and weight allowed larger screens albeit at the cost of picture quality and brightness. Front-projection systems, also based on CRT technology provided another route to larger television images for the consumer.

A number of competing flat screen technologies began to be introduced in television sets from the late 1990s. The primary types were Liquid Crystal Display (LCD), Plasma Display Panel (PDP) and Light Emitting Diode (LED). Early screens were expensive and could not compete with the pictures provided by CRT technology. However flat screens gained a foothold in the computer display market [32]. Gradually falling prices and significant improvements in image quality and screen size closed the gap in performance between flat screen televisions and CRTs to the point at which CRTs disappeared from the consumer television market. Improvements in flat panel technologies continue and new developments, such as Organic Light Emitting Diode (OLED) panels and Quantum dot integrated LEDs have brought the promise of higher contrast ratios, wider colour gamut and the ability to cope with faster frame rates than ever before [33].

Flat screen technology has broken the constraint on screen size for direct-view television that existed under CRT. Televisions with screen sizes well in excess of 50 inches are now widely available and are comparatively inexpensive. Several televisions with 100 inch and larger screens are also currently available. Projection also continues to offer an alternative option for providing television images in the post-CRT age, with a large number of projectors based on technologies, such as Digital Light Processing, now available to consumers.

Stereoscopic 3D televisions began to appear on the market during the last decade. These televisions use a number of techniques mostly requiring the viewer to wear glasses with filters or shutters although some screens that use auto stereoscopy techniques in which the viewer does not require glasses have now been developed. 3D televisions proved popular for a few years, with 3D movies being released on Blu-ray and some broadcasters offering 3D programming, but consumer interest has now started to decline [34].

2.8 Consumer Video Formats

The arrival of the Video Cassette Recorder (VCR) in the late 1960s led to a change in viewers' relationship with television. Television programmes no longer had to be watched as and when they were broadcast. Consumer interest in video recording was low at first but escalated with the introduction of the Betamax and VHS formats in the mid-1970s. These formats offered approximately 250 lines of resolution (this term is explained in section 3.2) compared to around 440 lines for broadcast. This quality was acceptable to consumers given the relative affordability of VCRs and the opportunities that they presented for time-shifting of television viewing and dealing with scheduling clashes.

In the 1980s, film studios saw an opportunity to generate revenue by releasing movies on pre-recorded video cassettes. VCR owners could rent the tapes from video libraries and watch the movies at home. This development and the decision by studios to favour VHS over Betamax was decisive in the bitter “format war” that had ensued between the two formats [35].

An alternative to video tape for pre-recorded material came in the form of optical disc based formats. Laservision (1978) was rebranded as Laserdisc in 1985 following audio enhancements but despite near broadcast quality video, these 12 inch disc formats never found favour beyond the niche home cinema enthusiast market. The Video CD, introduced in 1993, became the first method for distributing digital video encoded in MPEG-1 format on 120mm Compact Discs (CDs). However video quality on these discs provided no improvement over VHS.

The Digital Versatile Disc introduced in 1995 delivered a far higher data capacity than CD. DVD-Video (DVD) used MPEG-2 encoding to provide two or more hours of video on a disc in a quality that was superior to any other format of the time [36, 37]. DVD was embraced by film studios which fuelled its success with consumers and has now replaced video tape as the primary physical media for distributing pre-recorded material. Blu-ray was developed as the basis for High Definition movie distribution along with the unsuccessful HD-DVD. The 120mm discs have higher capacities than DVD and encode material using MPEG-4. DVD and Blu-ray currently sit side by side as consumer formats.

Video tape’s days as the primary method for recording television were numbered following the introduction of Personal Video Recorders (PVRs). Early PVRs such as Tivo, released in 1998, digitally encoded analogue television signals for recording to a Hard Disk Drive (HDD). Later PVRs have been integrated into set top boxes and directly record the DTV streams to HDD. The use of HDDs brings two major advantages over systems using removable media:

1. The high storage capacity offered by HDDs mean that it is possible to record many hours of programming without the need to change media.

2. Faster access and data rates mean that simultaneous recording of multiple programmes can take place at the same time as play back. This also permits the pausing and rewinding of live television.

2.9 Games Consoles

Prior to the release of the Magnavox Odyssey in 1972, the television set's only purpose in the home was to display television pictures. While the Odyssey was a simple fully analogue device it was the first in a long line of games consoles that have made increasing use of the quality and definition available in televisions [38]. Later consoles have provided support for DVD and Blu-ray allowing the machines to serve a dual purpose as games machines and video players.

2.10 Television in the Internet Age

The last twenty years have seen a gradual merging of television and internet technologies. Software and hardware to encode and decode digital video became available making it possible to view media including DVDs on computers. Television decoder cards allowed computers to be used as video recorders and television displays. Websites such as YouTube allow users to upload and view material that might have previously been viewed on a television. Higher bandwidth internet connections and improved compression algorithms, such as MPEG4-H.264, allowed an increase in quality of video being shared on the internet. Advances in mobile communications and smartphones brought the internet and television out of the home.

Television broadcasters saw opportunities to provide video on demand and deliver programming and supplementary material to viewers via the internet. Companies including Netflix and Amazon began streaming movies and other material to users over the internet for a premium. Television programmes such as Netflix's *House of Cards* are now being specifically produced for internet television services. Television manufacturers began to offer internet connectivity on new televisions providing support for services such as YouTube and

Netflix. The large-scale changes that have been seen in the last ten years have led some television and video industry commentators to question whether television will survive the coming decades [39-41].

2.11 Chapter Summary

Chapter 2 explores the history of television from a technological standpoint with the aim of identifying examples of both successful and unsuccessful innovations that have impacted the development of television standards as they exist today. The dominant theme is that the history of television has been one of continual enhancement. This has largely been driven by the desire to provide viewers with improved image quality and increased choice in how, when and where material can be viewed and continues today with the introduction of UHDTV which is discussed in Chapter 3.

Chapter 3 - Definition and Standards

Definition is a term that has been used with regard to television since its earliest days. In essence, definition is a measure of image sharpness. It can be affected by a number of factors e.g. the number of lines or pixels making up an image, the scanning method (interlaced or progressive), the frame or field rate, the contrast range and the colour gamut. Various systems throughout the history of television have been stated to be “High Definition”. The 525-line and 625-line systems that predominated the latter part of the twentieth century were at the time of their development considered to be High Definition for example [42]. The development of higher definition systems from the 1980s onward led to the existing systems being rebranded as Standard Definition (SDTV), while the next range of higher resolution standards were defined as High Definition (HDTV). A new range of Ultra High Definition (UHDTV) standards are now being defined. This chapter examines these standards and the relationship between them to provide a basis for considering the challenges and opportunities for UHDTV in Chapter 4.

3.1 Aspect Ratio

Aspect ratio is the ratio of a display’s width to its height. The majority of electronic systems that were used to provide television services worldwide from the mid-1930s used an aspect ratio of 4:3 [42]. The NTSC gave significant deliberation to the choice of aspect ratio in 1940 based on physiological, aesthetic and technical considerations, before selecting the aspect ratio that had become standard during the early days of cinema. As television was settling on 4:3, aspect ratios had begun to widen in the motion picture industry, partially driven by a desire to differentiate the product from television as a result of falling cinema attendances.

The aspect ratio of 4:3 remained the standard for television until work towards the next generation of higher definition television pictures in the 1980s presented the first realistic opportunity for its reappraisal. An aspect ratio of 16:9 had been suggested as something that had a number of technical benefits due to its $^4/_3$ relationship with the existing television ratio. It was also close to the most commonly used aspect ratio in the cinema and provided a $^4/_3$ relationship with the 2:35:1 super wide formats such as Cinemascope used by the motion picture industry. Although some other aspect ratios were proposed and implemented in early HDTV systems, 16:9 became the standard around the world [43, 44].

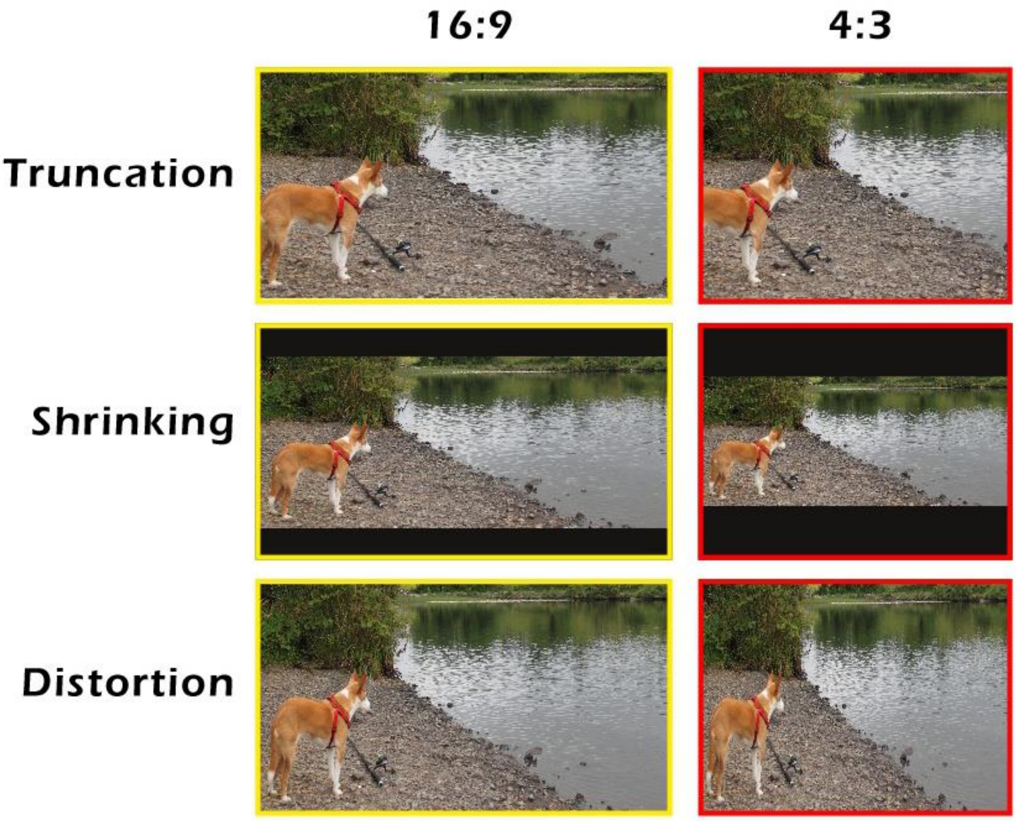


Figure 7: Alternatives for displaying a 2.35:1 image in 16:9 or 4:3 aspect ratios.

Displaying material in a different aspect ratio from which is has been shot or produced requires some form of compromise. Three techniques can be used (either alone or in combination) to achieve this:

1. Truncation – this involves cropping the image vertically or horizontally to fit the screen. Thus the entire screen area is utilised for display but parts of the image are lost. When modification of the aspect ratio takes place in real time, the area shown is usually centred on the original image. However if material is being prepared for later broadcast or mastered for a pre-recorded format, a pan and scan technique may be used to keep key parts of the image on screen.

2. Shrinking – this involves reducing the image while maintaining the original proportions, so it fits on to the screen. This method results in black bars at the top and bottom (letterboxing) or at the sides (pillarboxing) of the image. Consequently a large proportion (often 25% or more) of the display area is unused and the definition of the images will be reduced by the same rate.

3. Distortion – this involves stretching of the image either horizontally or vertically to fit the new aspect ratio. This method fills the display and retains all of the original image, but will stretch or squeeze everything within it.

Prior to the introduction of widescreen 16:9 television displays. The choice of how to handle aspect ratio changes were solely in the hands of the broadcasters and content providers. However modern television sets offer the viewer options to adjust the display to suit different aspect ratios under a number of guises.

3.2 Definition and Lines in the Analogue Era

Analogue television systems work by scanning and rendering an image as a series of horizontal lines. However the number of scan lines in analogue television is not equivalent to the vertical resolution of the images displayed. This is because a number of scan lines are not rendered to the display in order to allow the electron beam of a CRT to return to the top of the screen after the bottom line is displayed. Therefore the 525-line NTSC and 625-PAL/SECAM systems actually display only 483 and 576 active lines respectively. The number of active scan lines are fixed for any given analogue format and represent the maximum vertical resolution of an image. However in practice the number of lines that can be resolved would be less than this because the scan is a series of separate spaced lines which will never align perfectly with an image. Thus the value for vertical resolution of analogue television is usually calculated by applying the Kell factor of 0.7 to the active line count.

The horizontal resolution of the analogue television image is a direct dependency of the bandwidth of the signal. It equates to the number of vertical black and white transitions that could fit within the horizontal width of the image, greater bandwidth permits more transitions. The horizontal resolution is specified as the number of lines of resolution (which should not be confused with scan lines) and is usually measured in terms of "Television Lines per picture height" (TVL/ph).

For broadcast of 525-line NTSC on 6 MHz terrestrial channels (with 4.2 MHz available for luminance signal) the effective resolution came out to 331 TVL/ph horizontally and 338 TVL/ph vertically. These figures equate to around 440 by 338 lines on a 4:3 aspect ratio television [45].

3.3 Definition and Pixels in the Digital Era

The digitisation of television pictures and the development of flatscreen display technology led to a change from dealing with scan lines and lines of horizontal resolution to discrete pixels that make up each field or frame of the image. Although standards for DTV were being developed with HDTV services in mind, formats based upon the existing analogue SDTV services needed to be defined. These formats needed to be compatible with existing display equipment standards. Thus formats with vertical resolutions of 480 pixels and 576 pixels were specified to closely match the number of visible lines in the 525-line and 625-line systems respectively. A horizontal resolution of 720 pixels was specified for both of these formats and aspect ratio could be set at 4:3 and 16:9. These formats specify an interlaced picture with frame rates that match their analogue counterparts for compatibility and are now generally referred to as 480i and 576i.

The development of HDTV specifications was undertaken independently a number of regions and resulted in several separate standards including ATSC and DVB (Section 2.6). Nonetheless there was a desire from the organisations involved to produce standards that were largely compatible. This view was shared by the United Nations (UN) who brought the interested parties together through its agency concerned with international agreement on wired and wireless communications, the International Telecommunications Union (ITU). A large variety of formats were proposed and considered for HDTV [46]. However standards developed primarily around two resolutions, 1920 x 1080 and 1280 x 720. [47, 48].

The problem of flicker that interlacing was introduced to solve (see section 2.2) related specifically to CRT displays. However interlacing introduces a number of artefacts of its own including interline flicker and line crawl [49]. The arrival of flatscreen displays presented an opportunity to introduce progressive scan display formats. Despite the advantages of progressive scan techniques within post production and for display purposes, there were still challenges within the field of television. Camera technology had moved away from using tubes toward Charged Coupled Devices (CCD). However the sensitivity of these devices at the time presented challenges for progressive scanning of High Definition images [50]. Ultimately it was decided that the SDTV and HDTV standards should feature both interlaced and progressive scanning options.

The ITU specified a family of twenty video formats to comprise the DTV specification using a range of horizontal and vertical resolutions with interlaced and progressive scanning (Table 1). These were based on the proposed and existing television formats and provided support for a range of frame rates [51-53]. Formats H-T are classed as Standard Definition and formats A-G are classed as High Definition. Formats C and D are often referred to as Full HD. The frame rates specified cover a range of variants based on the analogue standards with the addition of 24 fps to match the standard used in cinema. The 23.976 fps rate applies the NTSC 0.1% adjustment to 24 fps frame rate for compatibility with the other NTSC rates. These formats are often referred to by their vertical resolution followed by an "i" or "p" to indicate if they are interlaced or progressive scan – e.g. 720p, 1080i etc.

				Aspect Ratio		Frame Rates (Hz)							
Format	**Resolution (Horizontal x Vertical)**	**Scan Method**	**Square Samples**	**4:3**	**16:9**	**23.976**	**24**	**25**	**29.97**	**30**	**50**	**59.94**	**60**
A	1920 x 1152	Progressive			•			•			•		
B	1920 x 1152	Interlaced			•			•			•		
C	1920 x 1080	Progressive	•		•	•	•	•	•	•	•	•	•
D	1920 x 1080	Interlaced	•		•			•	•	•			
E	1920 x 1035	Interlaced			•				•	•			
F	1440 x 1152	Interlaced			•			•			•		
G	1280 x 720	Progressive	•		•	•	•		•	•		•	•
H	720 x 576	Progressive		•	•			•			•		
I	720 x 576	Interlaced		•	•			•			•		
J	720 x 480	Interlaced		•	•				•	•			
K	720 x 480	Progressive		•	•	•	•		•	•		•	•
L	720 x 483	Interlaced		•	•								
M	720 x 483	Progressive		•	•	•	•		•	•		•	•
N	704 x 576	Progressive		•	•			•			•		
O	704 x 576	Interlaced		•	•			•			•		
P	704 x 480	Progressive		•	•	•	•		•	•		•	•
Q	704 x 480	Interlaced		•	•				•	•			
R	640 x 480	Progressive	•	•		•	•		•	•		•	•
S	640 x 480	Interlaced	•	•					•	•			
T	352 x 288	Interlaced		•	•			•					

Table 1: Video formats specified for Digital Terrestrial Television Broadcasting under ITU-R BT.1208-1 recommendation

3.4 Standards Conversion

The move from production of programming in analogue to digital and SDTV to HDTV was a gradual process as television companies upgraded their equipment. This requires the conversion of material into different formats with potentially different image resolutions, aspect ratios and frame rates. In addition conversion between interlaced and progressive scan formats and the different colourimetries of the digital and analogue formats needs to be taken care of. The process of converting analogue material to a digital format is called upconversion. Upconversion may involve upscaling to increase the resolution of the image or the move from interlace to progressive scan through interpolation methods to generate additional pixels. The reverse processes of generating analogue from digital and SDTV from HDTV signals are called downconversion and downscaling. There is a tendency for the terms upconversion/upscaling and downconversion/downscaling to be used interchangeably by technicians, equipment manufacturers and researchers.

In the digital age of television, conversion of signals and scaling of images can be performed by consumer equipment or at the production end of the television chain. Set top boxes receiving digital HDTV signals may output to a variety of consumer equipment over analogue or digital connections requiring downconversion or upconversion. Similarly it is not uncommon for modern consumer equipment to provide facility to upscale lower resolution images to the higher display resolution of the television. The need for standards conversion may result in the television signal going through a number of conversions at different stages between capture, post-production, broadcast and display. When lossy compression is applied to the digital material in conjunction with these conversions there is a significant challenge to ensuring that the final television image is not degraded. [54-57].

3.5 Ultra High Definition Television

Ultra High Definition (UHD) is the label given to the next set of resolutions beyond the HDTV formats with picture widths beyond the 1920 pixels of Full HD. Currently two standards have been approved by the ITU for UHD television (UHDTV). The standards specify two resolutions UHD-1 which is 3840 (horizontal) x 2160 (vertical) pixels and UHD-2 which is 7680 x 4320 pixels [3]. The two standards are also widely known as 4K and 8K, which is a reference to their approximate horizontal resolution. This labelling by horizontal resolution presents a departure from the previous convention within television of using a measure of vertical resolution (e.g. 525-lines or 1080p). Both 4K and 8K were developed as standards for digital cinema applications where the convention did not apply. Many equipment manufacturers have adopted the 4K moniker for their UHD-1 products which has resulted in the name sticking. UHD-1 quadruples the number of pixels over Full HD and UHD-2 quadruples the number of pixels over UHD-1. Using this scaling factor simplifies upscaling and downscaling content between HD and UHD spatial resolutions.

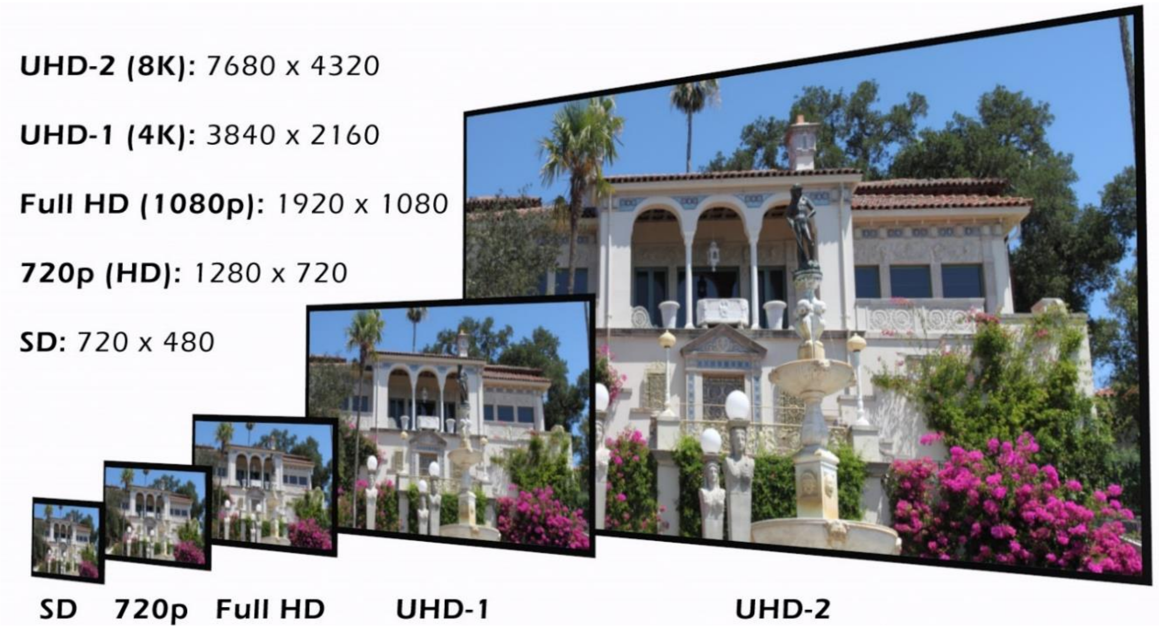


Figure 8: Comparative resolutions of the UHD formats compared to HD and SD TV resolutions

Both the UHD-1 and UHD-2 standards are specified as progressive scan only but all frame rates available for 1080p are present. The UHD standards also add frame rates of 120 fps, 119.88 fps and 100 fps giving the possibility of significant increase in temporal resolution over that offered currently HDTV. This has the potential to reduce motion blur on fast moving objects. The recommendations also specify a greater bit depth of at least 10 bits (optionally up to 16 bits) giving an improved dynamic range over the 8 bits used for HDTV. In short this allows a greater range of contrast between dark and light allowing for a reduction in the effects of posterisation that can affect digital video. Additionally an expanded colour gamut over that specified for HDTV is included. All of these improvements are aimed at bringing a more immersive experience to television for the viewer. Some of the parameters for UHD are still under discussion but it is clear that increased resolution, increased frame rate and increased bit depth all require more bandwidth. Some of this should be offset by use of High Efficiency Video Coding (HEVC or H.265), which has been shown to be significantly more efficient in terms of compression than previous codecs such as H.264. [58, 59].

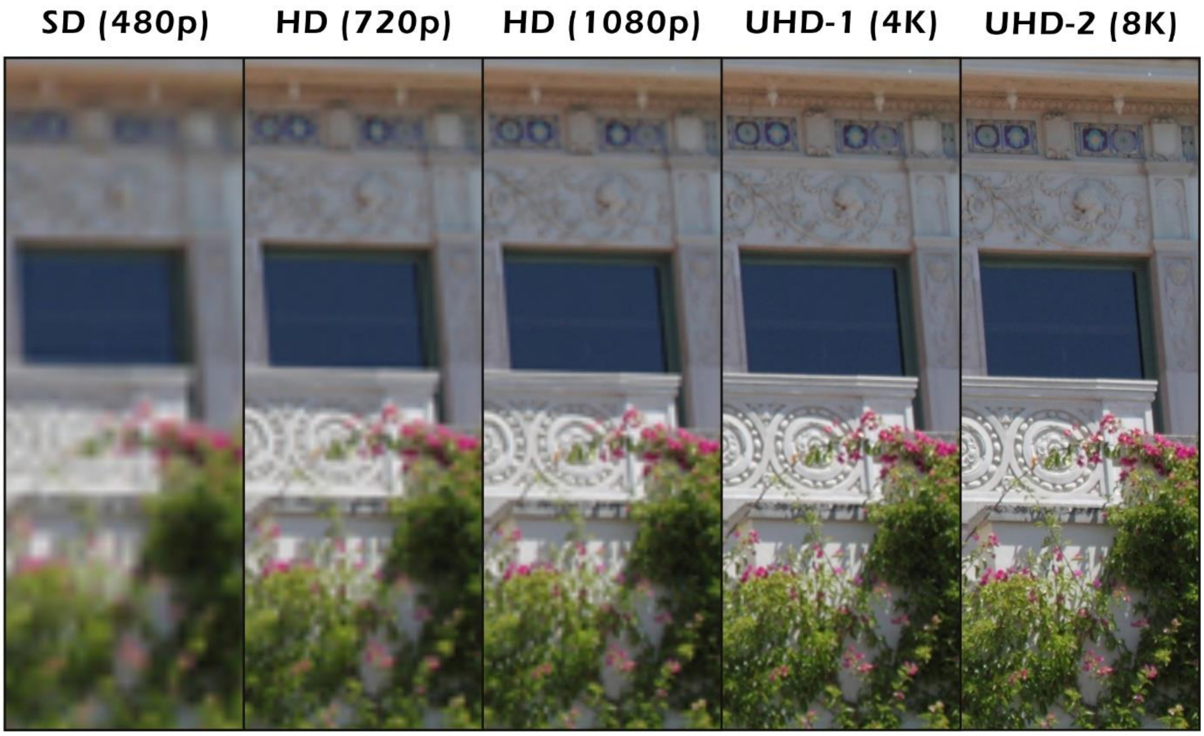


Figure 9: Comparison of the varying spatial definition offered by different television formats.

As of April 2015 the UHDTV standards are yet to be finalised and some of the parameters that have been outlined above are still subject to change. However televisions displaying 4K resolution are already widely available with screen sizes ranging from 40 inches up to in excess of 100 inches. Computer monitors and projectors with 4k resolutions are available and will soon be joined by smartphone screens [60]. This means that the wide range of screen sizes that HD material can currently be viewed on will also apply to UHD-1.

3.6 UHD Material

While 4K display devices are readily available, UHD material to view on these devices is currently scarce. Currently those seeking UHD material are limited to transmissions from the handful of broadcasters who are offering UHD services or to premium internet streaming services like Netflix Ultra HD 4K and Amazon Ultra HD [61]. Internet streaming requires significant bandwidth. Netflix recommend a minimum internet connection speed of 25Mb/s to stream UHD. Netflix also state that their service is not compatible with all 4K devices [62].

The Blu-ray Disc Association (BDA), a consortium whose responsibilities include developing standards for the format, are currently working on a revised specification for Blu-ray. This will provide support for 4K resolution at up to 60 frames per second with an increased bit depth of 10 bits and a wider colour gamut than the current Blu-ray High Definition standard. Though current disc capacities of up to 50GB are large enough for many requirements, it is also expected that the new specifications will include larger capacities and faster data rates to allow for less compression. As of early 2015, there is general expectation that players and media using the format will be available by the end of the year. [63-65].

With 4K television in its early infancy the thought of 8K transmissions might seem fanciful. Nonetheless Japanese broadcaster NHK are developing an 8K resolution television service called Super Hi-Vision with plans for test broadcasting via satellite in 2020 [66].

3.7 Screen Size, Viewing Distance and Viewing Angle

The improved spatial resolution in the UHD formats can unquestionably provide a sharper image than the resolutions of SD or HD as can be seen in Figure 9. However the extent to which the improved resolution can be perceived by a viewer is dependent on the size of the pixels making up the image and the distance of the viewer from the screen. Visual acuity varies between people, however the recommendation ITU-R BT.1845-1 suggests that in general individual pixels cannot be delineated by a viewer at a visual angle of less than one arc-minute [67]. This equates to a linear relationship between screen size and viewing distance based on the screen resolution as shown by the solid lines in Figure 10.

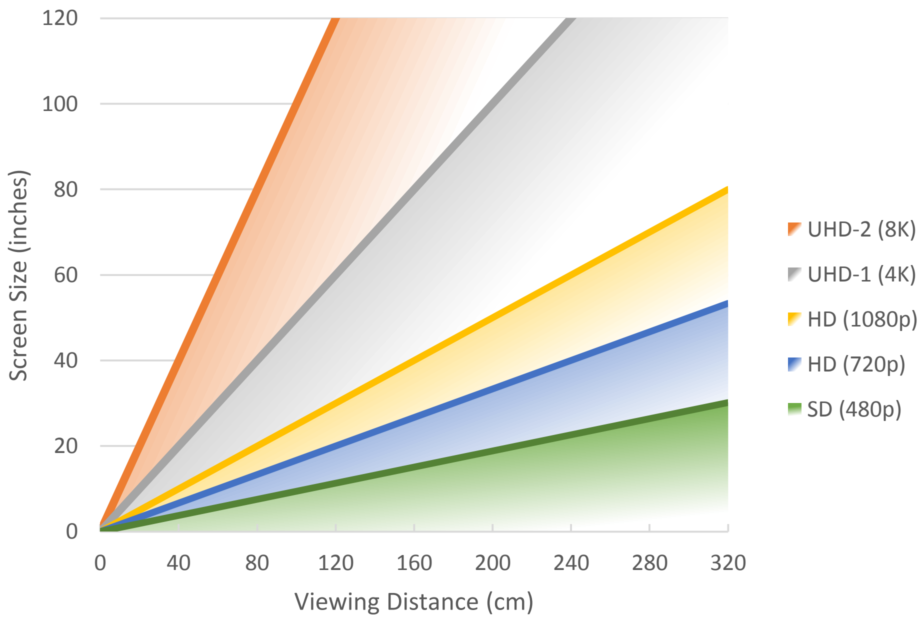


Figure 10: Relationship between optimal viewing distance and screen size for UHD, HD and SD formats

The area below and to the right each line is the optimal distance and screen size relationship for each format. Thus there is clearly no benefit in the increased spatial resolution offered by the UHD formats for small to medium screen sizes at relatively long distances. For example, the typical distance for a viewer to watch a television set is 2-3m. At 2m the smallest UHDTV screen size that would give a discernibly better spatial resolution than its HDTV equivalent would be of the order of 50 inches.

The benefits of UHD screen resolutions become apparent at wider viewing angles. ITU-R BT.1845-1 provides a method for calculating the optimal viewing distance in terms of picture height and the corresponding horizontal viewing angle. Figure 11 graphically represents the viewing angles for different formats. The wider field of view afforded by UHD resolutions is seen as a way of increasing viewer immersion in television [2, 68]. The relationship between pixel size and viewing distance applies equally to large projected images and to small screens such as on mobile devices.

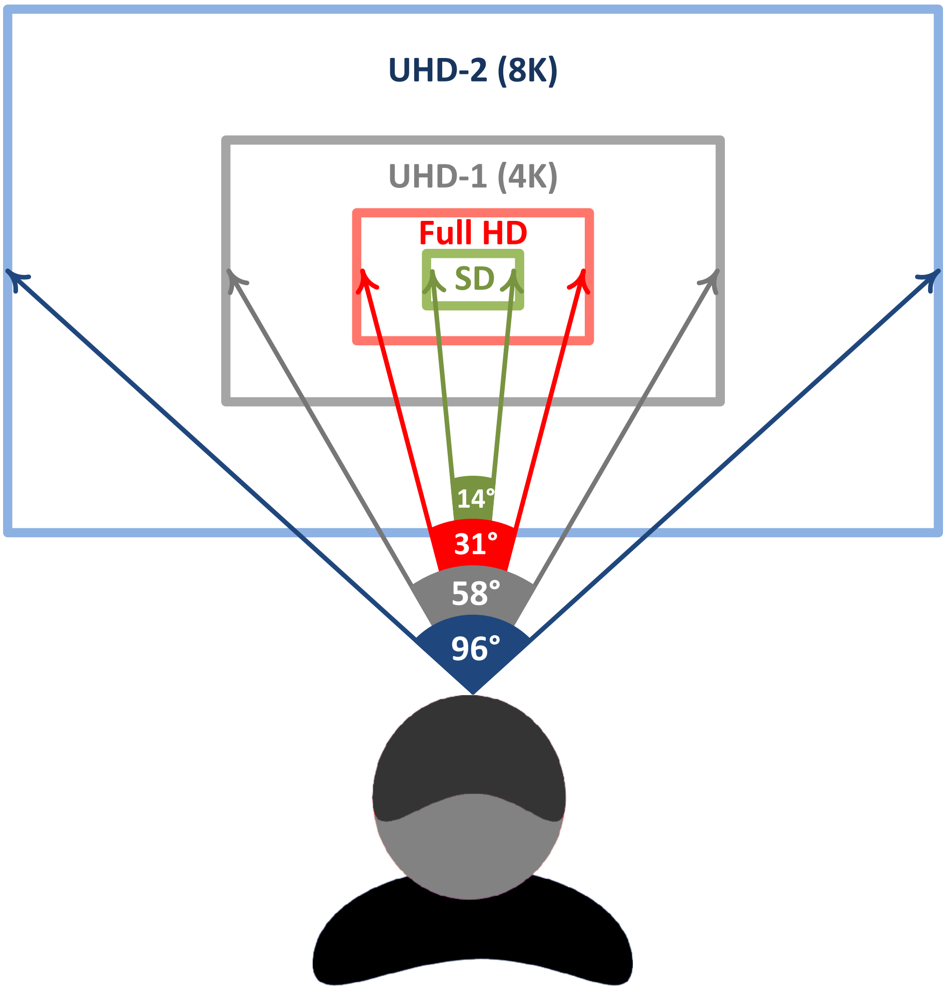


Figure 11: Optimal horizontal viewing angles for SD, HD and UHD television formats

3.8 Chapter Summary

Chapter 3 examines the standards that are defined for SDTV, HDTV and UHDTV and how these specifications relate to each other and legacy analogue television standards. UHDTV continues the tradition of improving picture quality in successive television standards. However availing of these improvements has implications in terms of the delivery and display of television. Chapter 4 identifies key challenges and opportunities for HDTV.

Chapter 4 - The Future of Ultra High Definition

This chapter identifies and explores the key challenges that stand in the way of UHDTV's widespread adoption and the opportunities that exist to attract viewers and content providers. These challenges and opportunities have been identified through careful study of the history of television as outlined in Chapter 2 and analysis of UHDTV's relationship to the other standards discussed in Chapter 3. The outcome of this research is presented in the following sections.

4.1 The Challenges to UHDTV

Table 2 lists the challenges to widespread adoption of UHDTV that have been established by this research together with the sections of this document containing material that informed their selection.

Challenge	Background Sections
Physical constraints	2.7, 3.7
Bandwidth requirements	2.4, 2.6, 2.10, 3.5
Lack of available content	2.7, 3.6
Too niche for the mainstream	2.8
Consumer confusion	3.5, 3.6

Table 2: Challenges to UHDTV attaining widespread consumer adoption

Each of these challenges are analysed in the sections that follow.

4.1.1 Physical Constraints

Utilising the additional spatial resolution available in UHD will present a challenge for many viewers. As explained in section 3.7, optimum viewing of UHDTV pictures requires a large screen or a short viewing distance in order to have the ideal viewing angle. This is suitable for a viewing space in which the presentation of an image with a wide field of view is primary, such as a dedicated media room. However in a typical residential scenario there are frequently physical constraints on television screen size and placement, in addition to aesthetic considerations. These matters are likely to make providing such a wide field of view a significant challenge, particularly when using smaller screens at shorter viewing distances for multiple seating positions within a room.

Curved screens represent a new trend in very large screen television sets. These attempt to lessen the difference in visual angle between pixels situated at the centre and the edges of the screen, which is of benefit with the wider field of view for UHD. These screens have a larger physical footprint than conventional flat screen televisions which has implications for wall mounting and the space taken up by the device.

Even in circumstances where an ideal combination of viewing distance and screen size for 4K material can be provided, viewing material at HD or SD resolutions will be compromised by pixilation at the same distance. This problem could be offset through upscaling of images. However the quality of the lower resolution image and the level of compression artefacts will influence the quality of upscaling [58]. Thus until a larger range of UHD material becomes available to viewers pixilation is likely to be an issue.

In some cases projection may offer a better alternative for the viewing of UHD material although this brings its own problems in terms of low lighting requirements and placement of flat screens.

4.1.2 Bandwidth Requirements

Providing infrastructure for the delivery of video at sufficient data rates is essential to the success of UHD. Even with advanced compression methods such as HEVC, UHD’s appetite for bandwidth is insatiable. The evaluation of the performance of video encoding at different data rates is an area of significant research [58, 69, 70]. Performance varies depending on source material but target bit rates in the region of 20 Mbit/s using HEVC is the minimum for 4K television at low frame rates (~30 fps or less) and low bit depths. Experiments suggest that minimum frame rates of 50-60 fps and bit depths of at least 10 bits are required to produce an immersive experience for the viewer at 4K resolutions [58]. Increases in temporal resolution and bit depth will require an increase in target bit rates accordingly. Similarly, 8K resolution will generate 4 times the data of its 4K equivalent. Thus target bit rates well in excess of 100 Mbit/s will be required for high specification UHD-2 broadcast or streaming.

The introduction of DTV and subsequent retirement of analogue broadcasting in many parts of the world has led to reallocation of parts of the broadcast spectrum for uses such as wireless broadband in many countries[71]. Consequently there is limited space for the addition of UHD channels to many existing terrestrial broadcast platforms without removing existing channels. Distribution of UHDTV signals by Satellite and Cable remains a possibility, although these platforms are not free of bandwidth constraints or costs.

The ability to stream existing 4K material to the home depends on the availability and performance of high speed broadband. Organisation for Economic Co-operation and Development figures for average and median advertised download speeds in 2012 suggest that download rates for many users in a large number of developed countries are well below the level required for streaming video at the required rates for UHD [72]. The fact that the actual sustained bandwidth of a connection may fall short of advertised speeds and the frequent need of users to share the bandwidth of a single connection for different uses can impact the viability of internet delivery of UHD services further. The demands on bandwidth by services such as UHDTV have led to concerns about their impact on existing services [73].

In light of large bandwidth requirements, there is the possibility of broadcasters and content providers using low frame rates or bit depths to conserve bandwidth. There is also the risk of using target bit rates that are not sufficient to prevent artefacts which would degrade the performance of 4K and 8K images and thus undermine the benefits of the enhanced specifications.

4.1.3 Lack of Available Content

Widespread adoption of UHDTV by consumers is dependent on the availability of sufficient suitable content. This requires the production of programming to UHD television standards and in turn the upgrading of infrastructure and equipment. A number of broadcasters have shown an interest in UHD and have conducted experiments using 4K or 8K resolutions [74].

In the analogue age broadcasters needed to support only one format at a time. Upgrades were carried out so as to be compatible with legacy television sets. Now television and video are delivered through a variety of platforms and watched on a wide array of devices. Content providers need to support an increasingly wide range of formats simultaneously. Adding

UHD to this mix requires more storage, transmission bandwidth and equipment with more processing power. The spatial resolutions of UHD-1 and UHD-2 are simple factors of the HD resolutions making scaling straightforward. However bit depth and temporal resolution differences and the need for colour gamut mapping place an additional overhead in downconverting UHD material [75].

Broadcasters showing an interest in UHD brings the promise of future services for those investing in 4K televisions but is not a guarantee of continued interest and long term UHDTV services. For example, the BBC started a pilot of 3D television in 2009. At this time 3D televisions had become available and sales were being buoyed by the success of 3D movies at the cinema and the Blu-ray format offering 3D compatible discs. A number of flagship BBC programmes were produced and broadcast in 3D as well as coverage of key sporting events including Wimbledon and the 2012 Olympic Games. However in 2013 the BBC abandoned the project citing a lack of interest from the British public [34]. This experience suggests that a handful of niche viewers would not be enough to sustain UHD broadcasting in the long term. There needs to be a substantial viewing base for UHD formats to be supported by a significant number of broadcasters.

4.1.4 Too Niche for the Mainstream

The Laservision/Laserdisc format (section 2.8) offered the best quality image and sound of any consumer video format at until the arrival of DVD. This quality helped Laserdisc to become the format of choice by home cinema enthusiasts but the formats were not successful beyond this niche.

There are also potential similarities between UHDTV and high definition audio formats which have become niche market products. The introduction of the audio CD heralded a revolution in the music industry similarly to the digital HDTV revolution in television. The CD was widely adopted by society. Since this, formats providing superior audio, such as Super Audio CD (SACD), have been developed. However SACD has been largely constrained to a small Audiophile market with little mainstream consumer interest. Consumers are now choosing to download music in formats such as MP3 at a lower quality than that offered by CD. This demonstrates that higher quality is not necessarily a substitute for the convenience and portability offered by low bandwidth formats.

Whether UHDTV is too niche a product for the mainstream depends upon one simple equation: For the average viewer do its benefits outweigh it cost.

4.1.5 Consumer confusion

UHD and 4K are currently popular terms in marketing television equipment. However behind the marketing hype these words can mean a myriad of things and have the potential to confuse consumers. While 4K televisions have the screen resolution to support UHD-1, the standards are about more than just pixels. Many 4K televisions do not support frame rates above 30 fps for example. Thus buying a 4K television does not guarantee compatibility with the full UHD-1 specification. The Consumer Electronics Association (CEA), a trade organisation of the consumer electronics industry in the USA, introduced logos for branding 4K displays that meet its own core characteristics in November 2014. While these characteristics are still short of the proposed UHD-1 specifications, these logos will identify equipment that meets minimum criteria for consumers [76]. There is also the potential for confusion from a "Mastered in 4K" range of Blu-ray releases that are currently available. Although the material on these discs has been mastered in 4K the format of the material itself is High Definition and therefore will show no improvement when displayed on a 4K display compared to a 1080p display.

4.2 The Opportunities for UHD

Table 3 lists the opportunities UHDTV has to attract viewers that have been established by this research together with the sections of this document containing material that informed their selection.

Opportunity	**Background Sections**
Sports broadcasting	3.6
Internet support and existing infrastructure	2.4, 2.6, 2.10 & 3.6
Closing the Cinema Gap	2.8 & 3.1
The Gaming Market	2.9

Table 3: Opportunities for UHD to attract viewers

Each of these challenges are analysed in the sections that follow.

4.2.1 Sports Broadcasting

Sport is one of the primary genres that stands to benefit from the immersive experience and sense of realism that UHDTV promises to offer. Figures reported by the Broadcasters' Audience Research Board in the UK [77] show that sport accounted for 7.6% of overall UK audience share for the nine months to September 2013. Trends in this report show that this figure waxes and wanes on a yearly basis. This is likely to do with the effect of large sporting events such as the FIFA World Cup and Olympics that are shown on Free to Air television in the UK but do not occur annually. Pay television sports channels command a much smaller share of the television audience, but the huge sums of money paid for the TV rights by both Free and Subscription broadcasters demonstrates the importance of sport to television viewers [78].

Sporting events can drive sales of televisions. The 2014 FIFA World Cup marked a boost in television set sales in the UK as viewers have upgraded to larger High Definition screens to watch the event [79, 80]. The week prior to the Super Bowl regularly sees an increase in television sales in the USA [81, 82].

Figure 12: Screenshot from Tata Sky website promoting their UHD 4K television service [83]

Of the broadcasters that are already providing UHD television services, sport is a very important part of programming and the drive for viewers. India's Tata Sky offered 4K resolution coverage of the 2015 ICC Cricket World Cup and cricket is at the forefront of the broadcaster's promotion of the format (Figure 12). Sky Deutschland tests of 4K featuring soccer have led to the suggestion that the format will change the way that the sport is filmed and presented, giving broadcasters the opportunity to cover games with less cameras for example [84].

4.2.2 Internet Support and Existing Infrastructure

The internet provides an avenue for viewers to avail of UHD material that did not exist for early adopters of the HDTV format. Viewers that bought HD ready televisions initially had to wait for HDTV broadcast services and the arrival of Blu-ray before their new screen could be used to its full potential. The provision of UHD services by Netflix and Amazon has filled the gap for many while the development of other services and UHD capable media takes place. Many satellite broadcasters have the potential to support 4K at current frame rates without significant upgrades to the delivery infrastructure. This has already led to the launch of some 4K services on satellite and the promise of more. [85]

4.2.3 Closing the Cinema Gap

Cinema has been threatened by television from the time that services were first introduced. The movie industry has ever since attempted to stay ahead of television through innovations designed set it apart. Many of these such as wider aspect ratios, multi-channel sound and even 3D have found their way into home viewing over time. Despite this, the one advantage that cinema has always held over television is its ability to immerse the viewer through high screen resolution images filling the viewer's field of view. UHD finally breaks this barrier using similar resolutions to those currently used in digital cinema applications and gives viewers the opportunity to better replicate the cinema viewing experience in their own home.

4.2.4 The Gaming Market

The potential of UHD to provide an immersive experience is an attractive proposition in the area of gaming. This is something that the console market will likely aim to exploit with new consoles that provide UHD compatible output. As of April 2015 there have been no announcements by any console manufacturers stating that they will support UHD platforms. However the success of recent consoles such as the PS4 and Xbox One suggest that console support could provide a significant incentive for gamers to invest in 4K screens [86].

4.3 Chapter Summary

Chapter 4 identifies and presents five key challenges that stand in the way of UHDTV's widespread adoption and four opportunities that it can leverage to attract viewers and content providers. These challenges and opportunities were identified through examination of television's history in Chapter 2 and analysis of the UHDTV standards and their relationship with both existing and legacy television standards as presented in chapter 3. Analysis of the implications of these challenges and opportunities to UHDTV is undertaken in Chapter 5.

Chapter 5 - Conclusions

This research paper has investigated the future of the fledgling Ultra High Definition Television (UHDTV) formats, UHD-1 (4K) and UHD-2 (8K), in the context of their relationship with legacy and existing television technology. Specifically the question:

"*What does the future hold for UHDTV, ubiquity or paucity?"*

was raised from my early insights on the technology.

The approach to evaluating this question has been to identify and analyse specific challenges that UHDTV faces in becoming an attractive proposition to consumers and opportunities that UHDTV could seize to achieve this goal. The process to identify and analyse these challenges and opportunities was based on two suppositions:

1. Events and technological innovations from television's history have had a bearing on the development of UHDTV and television as a medium today and will therefore have a bearing on UHDTV's future.
2. Understanding the benefits and demands of the UHDTV standards requires consideration of their relationship to HDTV and legacy broadcasting in terms of image quality and implications for production, delivery and display.

Chapters 2 and 3 present the material that was used as the basis for this analysis. Chapter 4 presents the five challenges and four opportunities for UHDTV that were found as a result of this analysis.

The challenges that UHDTV must overcome to find widespread consumer success are:

1. The physical constraints of utilising optimal UHDTV displays in the home.
2. The bandwidth requirements of UHD content delivery.
3. The current lack of available UHD content.
4. The risk of UHDTV becoming a niche product.
5. The risk of consumer confusion about UHD and device capabilities.

The opportunities that UHDTV can use to attract viewers are:

1. The live broadcasting of popular sports events.
2. The delivery of live broadcast and video on demand through existing platforms including the internet and satellite.

3. The similarities between large screen, wide field of view television and cinema.
4. The gaming market.

Many of the challenges faced by UHDTV are not dissimilar to challenges that have been faced in television's past. Compatibility issues and consumer confusion about new technology have accompanied television's upgrade to HDTV and digital services. Similarly a lack of available HDTV material affected early adopters of HDTV sets. These problems were resolved over time as knowledge increased and HD material became available.

Issues of bandwidth provision have equally been a problem throughout the history of television. Bandwidth constraints placed on broadcast channels limited the resolution of analogue television. Limited bandwidth in consumer video tape reduced quality also. The bandwidth required for DTV was a barrier to its implementation for broadcast until the development of techniques for DTV signal compression were developed with the introduction of MPEG encoding. Increases in the internet data rates available to many consumers over recent years suggest that over time bandwidth will become less of a problem for many consumers, particularly in urban areas. Satellite broadcasters adopting UHD will help to bridge the gap for viewers in more remote areas where the required internet speeds are not available.

Thus the three challenges of bandwidth requirements, lack of available content and consumer confusion should not ultimately be a barrier to UHDTV services. The other challenges of the physical constraints and the risk of UHDTV becoming a niche product remain however.

There can be no argument that UHDTV has the necessary parameters to allow for a significant increase in the quality of viewing over HDTV. The benefits of increased temporal resolution, dynamic range and colourimetry may be noticed regardless of screen size and viewing angle on a television set that implements those parameters fully. However the improvement in spatial resolution will only be seen at the relevant viewing angles. The optimal field of view for 4K pushes the current paradigm of home television as a display panel in the corner or on the wall of a room to its limits. If there is no significant discernible benefit to a user then there is little point in paying any premium for UHDTV.

It is for this reason that I believe UHDTV will be a niche product in the home until either the paradigm shifts significantly or UHDTV no longer commands a premium in the cost of hardware or UHD material.

The niche market that UHDTV will occupy is suggested by some of its opportunities. Home cinema is the obvious choice given that UHDTV's wide viewing angle is perfectly suited to the home theatre. Home cinema enthusiasts have a history of supporting high end formats that bring the best quality picture and sound and are willing to pay a premium to do so. Serious gamers are also likely to embrace the format if future versions of consoles and games that make use of the additional resolution. Sports broadcasting while having a track record of attracting viewers to HD, is probably not enough of a draw to support a niche on its own. However the availability of major sports events in UHD will be essential to the format if UHDTV is to find its way into the average home.

This research has identified challenges and opportunities to UHDTV becoming ubiquitous in the home. The conclusion that UHDTV's future is as a niche product is based on a loosely defined concept that I call the *paradigm of television in the home*. This concept merits further research as its understanding is essential to predicting exactly how television will be watched in the future and what place UHDTV will occupy in that future.

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