Impact of Packet Loss on 4K UHD Video for Portable Devices

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Abstract Ultra High Definition (UHD) video streaming to portable devices has become topical. Two standardized codecs are current, H.264/Advanced Video Coding (AVC) and the more recent High Efficiency Video Coding (HEVC). This paper compares the two codecs' robustness to packet loss, after making allowances for relative coding gain. A significant finding from the comparison is that the H.264/AVC codec is less impacted by packet loss than HEVC, despite their differing coding efficiencies and including at low levels of packet loss. The results will be especially relevant to those designing portable devices with 4K UHD video display capability, allowing them to estimate the level of error concealment necessary. The paper also includes the results of HEVC compressed UHD video streaming over an IEEE 802.11ad wireless link operating at 60 GHz as a pointer to future performance in an error-prone channel.

Keywords 4K UHD; H.264/AVC; HEVC; IEEE 802.ad; packet loss visibility

1 Introduction

Ultra-High Definition (UHD) 4K (3840 × 2160p pixels/frame, 16 × 9 aspect ratio) video transmission by Digital Video Broadcast terrestrial second-generation (DVB-T2) transmission was showcased at the 2014 Broadcast Asia conference. Compression with compression by the High Efficiency Video Coding (HEVC) standard codec [48]. An HEVC codec can provide 50% or more bitrate savings over the previous H.264/Advanced Video Coding (AVC) standard for higher resolutions up to UHD [62]. However, there also may be a drawback arising from greater compression efficiency because of a greater exposure to packet loss. It appears that a differential quality response to packet loss [4] can occur even at low loss rates. Therefore, this paper seeks to show that employing a more efficient codec for 4K UHD video, HEVC, may result in a relatively lower video quality than a less efficient codec, H.264/AVC, once packet loss is taken into account and coding gain is allowed for. The packet loss response to HEVC streaming over a 60 GHz IEEE 802.11ad wireless LAN (WLAN) is also of interest because there the potential bandwidth, 7 Gbps, which is unlicensed, is more suitable for higher resolution streaming than 5 GHz IEEE 802.11ac at 1 Gbps, though it is subject to oxygen absorption, requiring beamed transmission.

This paper's main finding, which will be relevant to designers of portable devices, is that the H.264/AVC codec remains useful whenever packet loss to 4K UHD video is a threat and live streaming of applications is undertaken. The alternative is the development of a more sophisticated form of HEVC error concealment than is present in the codec's reference software (see Section 3.1). The topic of HEVC error concealment is returned to in Section 4.3. The trend towards higher spatial resolutions has taken in mobile and portable devices [2]. System-on-chip designs have been developed [34] for high-definition (HD) video on smartphones. HD video has a 3.1 × picture height viewing distance, compared to 7.1 × picture height for Standard Definition (SD) [49]. Thus, HD video is particularly appropriate for portable displays, which are viewed close to. (The viewing distances reported are those at which the scan lines first become invisible.) Beyond High Definition (HD) [70], HEVC 4K UHD hardware processors are now being designed for mobile applications. For example, 4K UHD can be output at 30 fps [29], with bitrates of 25 or 50 Mbps with either maximum 32 × 32 or 64 × 64 Coding Tree Blocks (CTB) respectively. However, when the 4K UHD encoder [29] was tested across a set of reference videos, the bitrate was on average 34.6% higher than the HEVC Test Model (HM-13.0) in Low Delay P mode, owing to the need to make rapid mode decisions [29] so as to reduce encoding overhead. Thus, the bitrates of that processor are above those of the tests in Section 5 of this paper, while the luminance video quality (measured by Peak Signal-to-Noise Ratio (PSNR)) is on average 0.5% below that arising from the reference software implementation, HM-13.0.

In general, users may expect portable displays to display similar broadcast quality video to that experienced on home TVs [6], especially when they are aware of the advanced technology of tablets and smartphones and possibly of cloud transcoding [31]. Despite such desires, in fact video is still delivered to portable devices over error-prone wireless networks. Pseudo-streaming with some form of HTTP Adaptive Streaming (HAS) can deliver error-free video-on-demand. However, when a wireless channel error occurs the underlying TCP re-transmits lost packets. Though the stream at the receiver is error-free, large buffers are needed. This implies start-up delay may affect short video clips, and, for longer video sequences, there is a risk of increased and annoying freeze frames, along with quality fluctuations [57]. End-to-end delay, added to by large buffers, is particularly apparent in interactive services including mobile: video gaming, teleconferencing, and telemedicine. If live 4K UHD video is encoded and transmitted between peer devices, TCP-based transmission may add intolerable delay.

On the other hand, if a native variety of streaming is employed, that is Internet Protocol (IP)/User Datagram Protocol (UDP)/Real-time Transport Protocol (RTP) or MPEG-2 Transport Stream (TS) within IP packets (at a cost in additional header overhead but for compatibility with broadcast video) packet loss will certainly affect the video quality. However, most evaluations of video Packet Loss Visibility (PLV) have considered video resolutions below or sometimes up to HD but not ‘beyond HD’. For example, Nightingale et al. [39], considered the impact of network impairments on HEVC encoded video streams below HD resolution.

When considering higher resolutions, the video quality after packet losses can be affected by changes in encoding format. Thus, it has previously been demonstrated [47] that H.264/AVC HD video quality falls dramatically for even very low packet loss rates (PLRs) (0.02%), while for MPEG-2 encoding of the same video, the quality drops by much less. The finding was, therefore, that for equivalent transmitted HD video quality [47] the older codec achieves a better quality at the receiver, once packet loss is factored in. Notice, however, that the Pinson et al. [47] experiments adjusted for the expected coding gain between MPEG-2 and H.264/AVC to allow the PLV of video of equal expected quality to be compared. MPEG-2 encoded video at 6 Mbps was compared with an H.264/AVC bit-rate of 2 Mbps. The same adjustment was also made [42] when inter-codec bitrate savings were compared across equal objective video quality.

From these findings [47] [42] one might take the view that there may be circumstances in which it may be feasible to use a less efficient codec for (say) reasons of cost, availability, and energy consumption, as well as resistance to packet loss. High-throughput wireless transmission under standards such as IEEE 802.11ac and short-range IEEE 802.11ad at 60 GHz [2] means that bandwidth/bitrate is less of a bottleneck for transmission of video compressed by a less efficient codec. In this paper, we mainly build-upon the earlier insight of [47] by considering whether the MPEG-2/H.264/AVC finding may transfer to the H.264/AVC and HEVC codecs at higher spatial resolutions. A two-page conference version of the current paper, i.e. [4], first drew attention to the design issue of choice of codec for emerging sports cameras and other portable devices supporting 4K UHD. In addition, to additional comparative results, the current paper also includes the results of streaming HEVC compressed video over an IEEE 802.11ad 60 GHz wireless link, which allows short-range video streaming over a wireless connection with ample bandwidth, though similar threats to received video quality from packet loss. Though this paper does not contain a technical innovation as such, it does contain insights as to how to handle the current push towards wireless transmission of ever higher spatial resolutions. In that sense, it is innovatory in its interpretation of current codec developments, especially in respect to 4K UHD streaming to portable devices.

The remainder of this paper is organized as follows. Section 2 sets the context in terms of 4K UHD video transmission, codec features, IEEE 802.11ad wireless, and video quality assessment after packet loss. Section 3 describes the video and experimental configurations for experimental tests, the results of which are described and analysed in Section 4. Lastly Section 5, summarizes the main findings, practical pointers that have emerged, and a future research direction.

2 Context

This Section concisely reviews the background to an understanding of the findings in this paper.

2.1 Transmission of 4K UHD

Video display at UHD can be achieved through commercial production of 4K UHD monitors, televisions, and beam projectors (at 4096 × 2160 pixels/frame (True or Digital Cinema Initiative (DCI) 4K)) [28], and now portable devices [2] [6]. Section 2.2 returns to the subject of the current existing ecosystem of 4K UHD-capable portable devices. Researchers have investigated streaming uncompressed 4K UHD video over optical networks [60] [16] (with an application in digital cinema). 2.39 Gbps is the minimal bandwidth necessary for uncompressed UHD video with 8-bit 4:2:0 chroma subsampling at 24 frames per second (fps) (with 3.98 Gbps for 8-bit 4:2:2 subsampling at 30 fps). In fact, 60 GHz transmission is vulnerable to absorption by oxygen in the air, severely limiting its effective range, which is why the feasibility of multi-hop 60 GHz transmission has been explored [1] and shown to be achievable with low latency. Transmission at terahertz frequencies (100 GHz-10 THz) has also been turned to [38] for 4K UHD uncompressed video. The frequency of 138 GHz was selected, as this lies in an atmospheric window with reduced absorption. However, in [38] the link distance was only 30 cm with 5% failed frames at 30 fps. Uncompressed video transmission avoids coding delay when streaming live video. Otherwise, the storage requirements are considerable. Thus, an uncompressed 4K UHD 30-minute video clip will require 537.75 GB of storage. Therefore, compressed formats are normally preferred.

Compressed UHD video transmission over optical networks, owing to their large bandwidths, has long attracted the attention of researchers. For example, in [59] a JPEG 2000 codec, without the delays arising from motion prediction, was deployed to compress/send or receive/decompress 4K UHD video with visually-lossless quality at bit rates of 200-500 Mbps over a 1-Gbps IP network. In [17], 4K UHD was split into a base layer (BL) and an enhancement layer (EL) for broadcast of video as two streams, with a rate-distortion loss of 10% to 30%. In exploratory tests, scalable 4K UHD video allowed either full HD to be decoded or 4K UHD to be decoded at a mean rate of 38 fps. It also potentially enables the 4K UHD twin streams to be transmitted over different wireless media, i.e. DVB-T2 and satellite. The feasibility of 4K UHD transmission over emerging 5G cellular systems was explored in [44]. It was observed that Long Term Evolution (LTE) (a type of broadband wireless technology for cellular systems) of broadcast video content across two channels did not provide sufficient bandwidth and latencies for HAS-type video communication were too high. Carrier aggregation could resolve those issues if, in the simulation testbed, wireless packet loss was turned off. However, packet loss rates of up to 10% were an issue at a receiver speed of 3 km/h. The effects could be mitigated if rateless channel coding through the RaptorQ coder was turned on, though this required a reduction of the video bitrate of up to 20%. Latency also increased by up to 20%. Elsewhere [55] a prototype scheme has been developed for the transmission of 4K UHD video across a 5G hotspot testbed. 5G hotspots are likely to be congested and the scheme considers how video transmission can self-optimize for the impact of that traffic congestion.

Although HEVC is well-matched to higher resolution video storage, an HEVC encoder is also significantly more complex [17] than an H.264/AVC encoder. Therefore, without a suitable hardware implementation, transmitted frame rates for UHD video may be restricted to 30 fps or below, with the added problem of excessive energy consumption if transmission is from a portable device even with that restriction. In fact, frame rates of 60 fps and higher are required [14] [62] to reduce motion blur and flicker at 4K UHD's wider Field-of-View (FoV), which is 60º in comparison to HD's 30º. If 4K UHD hardware encoders are then, for HEVC encoding, rapid coding mode decisions are needed at present to reduce overhead from checking the distortion at every possible coding mode. However, in [29] rapid coding mode decisions resulted in 34.6% higher bitrates for the equivalent video quality arising from HM-13.0 codec's Low Delay P mode. Thus, rapid coding mode decisions may well result in higher bitrates.

As an alternative to a hardware codec, hardware acceleration has been investigated. In [71], four H264/AVC components were ported to the Compute Unified Device Architecture (CUDA) for parallel processing on Graphical Processing Units (GPUs). Data localization improved thread performance on a GPU. However, limitations still existed: the approach was not suited to UHD video resolutions and to GPUs with restricted local memory. Another problem was the excessive latency occurring due to a requirement to transfer data back and forth from the CPU main memory. Hardware can also be applied to converting lower resolution video content to UHD content, as the lack of such content is an impediment to broadcast services. For example, in [24], a convolutional neural network, implemented on a Field Programmable Neural Network (FPGA), converted 2K content to UHD content. Paradoxically, in [27], the assumption was that 4K UHD video may need to be retargeted to a lower resolution for smartphone displays and consequently the authors, who are transcoding experts, provide ways of doing this. However, Section 2.2 describes smartphone manufacturer interest in directly supporting 4K UHD video, other than lower resolution versions of UHD content.

Apart from, H.264/AVC and HEVC, the VP9 codec (developed as open and royalty-free by Google prior to the emerging AOMedia 1 (AVI) codec) is a popular alternative. However, in both [52] and [53], HEVC's compression performance versus VP9 was found to be markedly superior for UHD resolution video content of natural imagery after objective and subjective quality evaluations were taken into account. On the other hand, VP9 was said to be competitive with HEVC at that resolution for synthetic, computer-generated imagery. In a further study [3] of higher resolution video sequences, i.e. five at 1920 × 1080 pixels/frame @ 30 fps and one synthetic sequence at 1920 × 1080 pixels/frame @ 24 fps, AVI from the Alliance for Open Media (AOMedia), was also found to provide greater compression compared to VP9 and comparable compression to HEVC, in terms of video configured for broadcast, when both objective and subjective quality evaluation was taken into account. However, [52], [53] and [3] were studies of comparative codec coding efficiency across a range of video qualities and did not account for packet loss. Because the close viewing distance may favor 4K UHD over HD video in an immersive environment [2], a cross-codec (H.264/AVC, HEVC, VP9) study of relative quality evaluation also appeared as [12].

2.2 UHD-Capable Portable Devices

A good number of smart phones such as the L5 G8, Huawei P10, Samsung Galaxy X8, and Google Pixel X8, to mention several randomly, can capture 4K UHD video. However, in general, some cameras may better capture a default resolution, such as HD, rather than 4K UHD. Because they are hand-held and may be used while moving, some form of stabilization is required to reduce motion blur, which is particularly noticeable at high spatial resolutions for video. Apart from camera motion and camera shake, another contributor to motion blur is the smaller light sensors on smartphones, which may not receive sufficient light to properly determine exposure times. If a longer exposure time results then motion blur will be accentuated. Of course, very rapid motion in the scene captured will also lead to motion blur but this is not easily dealt with. Optical image stabilisation involves compensatory motion of the light path to the image sensor, often by movement of the camera lens by reference to a motion sensor. A gyroscope motion sensor can be effective and is used within at least one current 4K UHD camera, though it does not compensate for any rotational camera motion. In-body image stabilisation involves moving the image sensor rather than the lens, with the motion determined by focal length measurements. Rotational motion can then be compensated for. Both optical and image stabilisation have their relative merits and demerits, cost being an important factor for smartphones. The latter may be a reason why current smartphone cameras, unlike some digital cameras do not as yet apparently employ dual stabilisation. A further class of stabilisation, which is more common in smartphones, is digital or electronic image stabilisation. To compensate for motion, the transition between video frames is smoothed over by introducing additional border to the edge of the image. This border is taken from an image buffer, with the pixels interpolated at the border edges during post-processing.

The ability to capture 4K UHD video and store it is not necessarily the same as to be able to display it. The Sony Xperia Z5 Premium, introduced into the marketplace towards the end of 2015, was the first to have a 4K UHD 5.5 inch screen with 2.5 hours battery life. The relatively short battery life of the Sony Xperia Z5 Premium at 4K UHD resolution illustrates a significant weakness of 4K UHD smartphones, which do require sufficient processing capacity, such as from Qualcomm's Snapdragon 800 chipset or updates to it. Though frame-rates supported are those of Standard Definition (SD) video, 24 or 30 frames per second (fps), in fact, for this resolution, visual artefacts are more apparent unless the frame-rate is 60 fps or higher [2]. Thus, the need to process 4K UHD frames at a higher frame rate is another impediment because it may too rapidly drain the battery. The GP1 chip for the GoPro Hero6 camera in 2017 is, however, said to be able to encode 4K UHD at 60 fps, with the more recent GoPro Hero7 camera said to have improved image stabilisation, though stabilisation does not operate at beyond 30 fps. Compression by the GoPro Hero6 and 7 is also through an HEVC chipset, though the chipset no doubt does not support the full functionality of the codec standard. Decoding is less onerous than encoding but nevertheless demanding and important if the display of 4K UHD video is to be extended to mobile devices. As early as 2013, DivX developers released information on HEVC decoding performance using an Intel i7 CPU at 3.5 GHz with 4 cores and 8 threads for 30 fps 4K UHD video. There have been many commercial HEVC hardware developments since then. To randomly select a few: In 2014, Apple announced the iPhone 6 and iPhone 6 Plus with support for HEVC for FaceTime over cellular networks; in 2015, Nvidia announced the Tegra X1 System-on-a-Chip (SoC) with full fixed-function HEVC hardware decoding; in late 2017, Intel launched their Pentium Silver & Celeron CPUs (Gemini Lake) for mobile (and desktop) products with full fixed function HEVC Main10 hardware decoding support. In 2018, Nvidia and Intel continued to refine their hardware support for HEVC.

In terms of wireless transmission, a good number of smartphones and tablets already support IEEE 802.11ac. For example, early commercial developments include: In 2012, Asus's ROG G75VX gaming notebook was said to be the first consumer-oriented notebook to be fully-compliant with the IEEE 802.11ac standard; in 2013, Apple announced that the new MacBook Air would have IEEE 802.11ac capability; as did Hewlett-Packard for its laptops, also in 2013. The first releases of IEEE 802.11ax, such as Samsung's Galaxy S10, are appearing at the time of writing. IEEE 802.11ax increases the bandwidth of IEEE 802.11ac by around 37% by features such as Orthogonal Frequency Division Multiple Access (OFDMA). It also includes measures to enable densification, the ability for separate wireless networks to co-exist in closer proximity. (Notice that Section 2.6 discusses IEEE 802.11ad). The IEEE standards are not the only means of transmitting 4K UHD video wirelessly [2]. Dell's Wireless Dock D5000 permits 60 GHz transmission with existing triband chips, with a maximum of 4 Gbps. The wireless dock was combined with the Dell Latitude 6430u Ultrabook with a 1601 WiGig network card in multi-hop 4K-UHD streaming experiments in [1].

2.3 Packet Loss Visibility

PLV [58] [5] assesses video quality according to the network response and in doing so may contradict assessments based on the bitrate and/or compression ratio, as we highlighted in Section 1 in respect to the comparison of codecs in respect to packet loss resilience. When comparing between resolutions rather than between codecs, differing opinions are evident. Some have observed [58] that packet loss is more visible at HD than at SD, because HD video occupies a wider field of view. However, in another study [5] it was opined that PLV in HD is much lower than in SD because the relative quantity of information carried in each packet is smaller. Thus, it is possible [5] that a lost packet affects less macroblocks (MBs) in HD video, and, consequently, results in less spatio-temporal error propagation. Following from this, developers should determine how packet structure impacts upon video quality, irrespective of bitrate differences, especially at UHD resolutions, when visual impairments may well be more apparent to the user than at lower spatial resolutions.

In subjective tests of H.264/AVC video [21], PLV was found to be dependent on: the initial mean-square-error between the error-free and concealed MBs in a slice; the maximum number of partitions of a block; and the frame-type, though other factors were also significant. It was found by the same research group working this time with MPEG-2 video [20] that small distortions of video quality arising from packet loss caused user dissatisfaction. Because motion-compensated error concealment was employed in the research in [5], the amount of motion present in lost packets was not such an important factor during video quality evaluation. Even so, from the current paper's perspective, that prior H.264/AVC work [5] was conducted with low-resolution imagery, namely Source Input Format (SIF) resolution (352×240 pixels/frame).

As mentioned in Section 1, Nightingale et al. [39] analysed the effect of network impairments upon HEVC encoded video streams, though below HD resolution, while another study did not extend beyond Common Intermediate Format (CIF) [22], possibly because of limitations imposed by the applications targeted. However, [39] did determine that packet loss above 3% would be unacceptable for HEVC compressed video viewers. Other works, as well as those for PLV [56] [5], have tried to identify factors that impact upon subjective video quality. For lower resolution video, research [9] has identified packet loss and bitrate to be more important than frame rate. Other research has also broadly examined [8] two factors: the data loss pattern; and the content characteristics. However, from the standpoint of resolution, the subjectively-tested video sequences were confined to SD (at 25 fps).

Furthermore, packet losses were mainly confined to I-frames [8], which reduces the relevance of the tests on PLV in other frames types, which predominate. When scene changes occurred, the encoder placed an additional I-frame within a Group-of-Pictures (GoP). Provided the error burst was not long enough to affect consecutive I-frames, scene changes curtailed temporal error propagation, thus, masking the long-term impact of PLV. Otherwise, the amount of I-frame PLV [8] was proportional to the error burst length. Camera zoom and pan have an opposite effect [51], increasing the distortion following on from packet loss. The data loss or error pattern [32], especially the number of packets affected, is also relevant for PLV analysis.

2.4 Types of Quality Assessment

In this paper video quality assessment is through objective MOS. Video streaming providers are normally not fortunate enough to have access to a panel of viewers [36] [40], mainly because of: time restrictions; cost; and the difficulty of bringing together a suitable set of viewers. Subjective testing also has practical weaknesses, as it does not permit a dynamic response to changes in the PLR or packet structures and is also not repeatable. However, objectively calculated ratings can approximate the results of subjective testing with a high degree of correlation.

The Video Quality Experts Group (VQEG) Full-Reference Television (FR-TV) Phase II tests [65] of the Video Quality Metric (VQM) [46] reported Pearson linear correlation coefficients (PCCs) with Difference MOS (DMOS) from subjective tests of above 0.9. Equally, after VQEG evaluation the Structural Similarity (SSIM) index also had a correlations well above 0.9 [37] and has outperformed four other models on a still image database [37]. Since the original SSIM presentation [67], a number of improvements have also been put in place. These correlations give good confidence that SSIM along with VQM are excellent objective measures of MOS. The result is that this paper has been able to present experimental results originally measured by either SSIM or VQM in one common objective MOS score. The results are repeatable and are arrived at in a practical manner, especially in respect to the reduced computation of SSIM.

An updated view of testing methods is available [63]. That investigation [63] broadly compared PSNR ratings to those of a 15-member panel of subjective testers. The main finding was that HEVC video quality up to UHD resolution is strongly influenced by the content tested. However, in terms of assessment, VQM was not employed because the computational cost was large, while SSIM and VQM were said to be not as popular as PSNR, which may be true but does not seem to be a strong reason not to use them. Though PSNR is straightforward to calculate, it is not directly related to human perception [69]. For example, PSNR does not account for the masking of distortion by the presence of texture, which SSIM does expose. However, elsewhere PSNR was again the basis of video quality assessment [10] for video streaming over a 'lossy' wireless channel. A method is specified [10] for applying PSNR across a video sequence with missing frames owing to packet dropping, which has good correlation with MOS. Nonetheless, one wonders why another metric was not used in the first place. Therefore, in this paper, objective MOS derived from VQM or SSIM is retained.

2.5 Standardized codecs

Key differences between the H.264/AVC [68] and the HEVC codec [42] standards, are presented in Table 1. These codecs are standardized according to the bitstream format output by the encoder and arriving at the decoder. The HEVC standard was designed with HD and UHD resolution video in mind. To achieve that goal, HEVC has introduced many coding refinements to reach the necessary compression ratios to stream video at higher resolutions over links with reduced bandwidth. Even though an HEVC codec implementation can reduce the bitrate by up to 50% compared to an H.264/AVC one, that advantage comes with an increase in codec complexity, which leads to increased processing delay, especially for a software rather than hardware or hardware-accelerated implementation. From the Table, both H.264/AVC and HEVC have drawbacks in respect to transmission of 4K UHD. In the case of H.264/AVC, possible low frame rates and bitrate overhead are obstacles. However, current HEVC implementations of live streaming also generally cannot support high frame rates for 4K UHD [2], unless modifications are made that might reduce the codec's bitrate advantage. The latter issues are further discussed in Section 3.

Table 1 Comparison between H. 264/AVC and HEVC standards

	Category	H.264/AVC	HEVC
General	Names	MPEG 4 Part 10 or H.264/AVC (Standardized in 2003)	MPEG-H, HEVC Part 2 or H.265 (Approved in Jan. 2013)
	Industry adoption	Dominant and accepted video codec for terrestrial, cable, satellite and IPTV broadcast. (ATSC/DVB/ISDB) Widely used for Blu-Ray, videoconferencing, mobile video, media players, video chat etc.	Implementation demonstration at NAB, IBC and other events starting in 2012 from companies e.g. ATEME, Broadcom, Thomson, Harmonic (Cisco), Ericsson, Qualcomm etc. Increased R&D across Encoder/Decoder /CE vendors for software and hardware based solutions
	Key Improvement	• 40-50% bit rate reduction compared to MPEG-2 • Led the growth of High Definition (HD) content delivery for Broadcast and Online	• 40-50% bit rate reduction at the same visual quality compared to H.264/AVC • Potential to realize UHD, 2K, 4K for broadcast and even online (Over The Top (OTT))
	Progression	Successor to MPEG-2	Successor to MPEG-4 Part 10 or H.264/AVC
Technical	Compression Model	Hybrid spatial-temporal prediction model • Flexible partition of Macro Block (MB), sub-MB for motion estimation • Intra Prediction (extrapolate already decoded neighboring pixels for prediction) • Introduced multi-view extension • 9 directional modes for intra prediction • Macroblock structure with maximum size 16×16 • Entropy coding by CABAC or Context Adaptive Variable Length Coding (CAVLC)	Extended hybrid spatial-temporal prediction model • Flexible partitioning, introduces Coding Tree Units (CTUs) (Coding, Prediction and Transform Units (CU, PU and TU respectively) • 35 directional modes for intra prediction • Superior parallel processing architecture, enhancements in multi-view coding extension • CTU supporting larger block structure (64×64 pixels) with more variable sub-partition structures • Entropy coding is only Context Adaptive Binary Arithmetic Coding (CABAC)
	Specification	Support up to 4K UHD Supports up to 59.94 fps 21 profiles; 17 levels	Support up to 8K UHDTV (8192 × 4320 pixels/frame) Supports up to 300 fps 3 approved profiles, draft for additional 5; 13 levels
	Drawback	Low frame rates/high bitrates *appear* unsuitable for higher resolutions.	Computationally expensive (~300% +) due to larger PUs and expensive Motion Estimation (intra prediction with more modes, asymmetric partitions in inter prediction)

2.6 IEEE 802.11ad

The IEEE 802.11ad amendment to the IEEE 802.11 standard was ratified in 2012 [41], with the WiGig industry-supported standard (WiGig^{TM}) integrated into it. As mentioned in Section 1, IEEE 802.11ad with four channels has a potential for bandwidths up to 7 Gbps by virtue of its higher transmission frequency but that potential for transmitting video at higher resolutions, possibly uncompressed, is available at a cost. Transmission at 60 GHz requires antenna beam-forming because oxygen absorption at a rate of 10 dB/km peaks at around 60 GHz [50]. IEEE 802.11ad pioneered the idea of virtual antenna sectors to regulate the selection of antennas to focus a beam. In [64], phase-weighted arrays were implemented as patch antennas within radio transceiver chipsets, i.e. making such arrays suitable for incorporation into consumer electronics devices.

Modulation over a single carrier can be relatively simple, given the high data rates anyway achievable at 60 GHz, Binary Phase-Shift Keying (BPSK) or Quadrature Phase Shift Keying (QPSK). Using Reed-Solomon (RS) channel coding distinguishes a low-power, single-carrier mode over using Low-Density Parity Check (LDPC) codes. Multi-carrier Orthogonal Frequency Division Modulation (OFDM) is a higher-energy alternative, not suited to the portable devices of this paper. Because directional beam-forming results in 'deaf' spots outside the beam, it is necessary to modify the IEEE contention-based MAC, which IEEE 802.1ad does by offering a choice of three solutions [13]. A polling-based solution is similar to IEEE 802.11's Point Coordination Function (PCF), hitherto defunct, but now adapted to directional beams. A time-scheduled allocation of access, likewise is similar to IEEE 802.11's Hybrid Coordination Function (HCF). Finally, 802.11ad also offers the usual CSMA/CA contention, provided a pseudo-omnidirectional beam pattern is employed. By 2016, notebooks such as the Acer TMP648-MG-789T had incorporated IEEE 802.11ad wireless interfaces as part of a 'triband' offering (with 2.4 and 5 GHz).

3 Experimental Methodology

3.1 Video configuration

To determine the relationship between PLV and spatial resolution, streaming experiments were performed so as to determine the effect of packet scheduling at the point in time when packet losses took place. The experiments tested 4K UHD along with Standard Definition (SD) and High Definition (HD) video. H.264/AVC and HEVC encodings were made through the well-known, open-source, and freely available FFmpeg implementations. Packet framing was by means of the MPEG2-Transport Stream (TS) prior to UDP packetization. The packet sizes were close to the Ethernet maximum of about 1.5 kB. Previous frame replacement was used for error concealment at the decoder so as to avoid complicating the interpretation by using a more sophisticated (and more computationally demanding and latency inducing) form of concealment. The same choice and for the same reason occurred in [32] in an influential study of packet loss patterns and is a common choice in such studies. In addition, error concealment was apparently omitted from the HEVC standard because it can cause unpredictable impacts upon highly-tuned prediction tools [56]. Notice though that frame level (though not slice level) error-concealment with pixel copy from the previous frame was implemented in the HEVC HM reference software. Therefore, previous frame replacement, as implemented in HM, represents a compromise between no error concealment in the HEVC standard and some form of H.264/AVC error concealment. Nevertheless, as HEVC keeps information about its collocated and adjacent motion vectors, motion copy is a natural form of error concealment to implement for an HEVC application, a topic returned to in Section 4.3.

The selection of source test sequence was constrained by the availability at the time of 4K UHD versions. Thus, 4K adaptations of well-known test sequences for checking codec characteristics were employed, except for the 15 min. computer-animated film Sintel, which was obtained from [7], with one frame from each video sequence illustrated in Fig. 1. Table 2 records the characteristics of the test sequences, of which the sample frames in Fig. 1 are extracted, in terms of recommendation ITU-T P.910's Spatial Index (SI) and Temporal Index (TI). TI can range from 0 to 80, with 0 meaning very limited motion and SI can vary from 0 to 250, with 0 implying very little spatial detail. The video sequences have been classified according to their motion activity, as represented by their TI values, which will impact on the encoder's computational complexity (and hence its latency). The spatial complexity of the video content is also an important determinant of encoding complexity, as a higher spatial complexity will reduce the video quality that can be achieved for a fixed bitrate. Foreman is a version of a well-known sequence that is used to test for the characteristics of typical sequences taken by hand-held cameras, characteristics such as jerky motion and rapid pan and zooms. Notice that Sintel is a very active film that serves as an alternative to the three natural sequences in terms of testing for PLV. Given that one of the applications of 4K UHD is streaming within an immersive environment, synthetic imagery ought to be tested.

In respect to transmission parameters, Table 3, the choice of the lowest Constant Bitrate (CBR) for 4K UHD video was arrived at by the approximate savings of 35.4% of an HEVC codec over an H.264/AVC codec [42]. This approximate savings estimate is adopted because it appears in a seminal paper authored by key players in the development of HEVC and, hence, is likely to be accepted by others. However, any savings estimate is video-content dependent and was estimated before the implementation of the HEVC encoder used in FFmpeg by us. Thus, the savings figure is likely to have increased and the reader is cautioned that, for those reasons, the figure used is, indeed, approximate. However, taking relative savings of 35.4%, a rate of around 13.5 Mbps for 4K UHD with an HEVC codec was arrived at, after an additional anticipated 0.1% PLR was factored in.

In Table 3, the GoP frame structures and sizes were selected empirically to arrive at the desired CBR bitrates, as previously identified. Though these bitrates were the main aim of the experiments, notice that an IPPPP… GoP frame structure is often adopted as a way of reducing processing at a resource-constrained portable receiver because of the additional computation and memory accesses involved when processing bi-predictive B-frames (as two reference frames rather than one are accessed). On the other hand, notice that employing B-frames, as for HEVC in the experiments, increases the compression ratio because motion estimation can be made more efficient.

The datarate for HEVC is below that of a hardware implementation [30] because: firstly fast mode decisions were not taken; and secondly the frame rate was 25 fps to accommodate the current WLAN bandwidth. The H.264/AVC frame rate was also 25 fps, which avoids a relatively more distant frame potentially damaging the quality during application of previous frame error concealment. However, a frame rate of at least 60 fps will be needed and possibly even 120 fps [71], hardware and bandwidth permitting, if a smooth viewing experience for 4K UHD is to be eventually achieved. In addition, to make UHD attractive compared to HD, an enhanced bit-depth of 12-bits per RGB channel, not the 8-bits used herein, is preferable. Though, some error resilience measures are available in the HEVC standard, they are limited in their scope compared to the H.264/AVC standard, making comparisons difficult. For the same reason, adding error concealment to the HEVC decoder, as is available, for example, in [15]'s reported implementation, which includes sophisticated error concealment and error resilience, would change HEVC's response to packet loss significantly but would make any comparison more problematic.

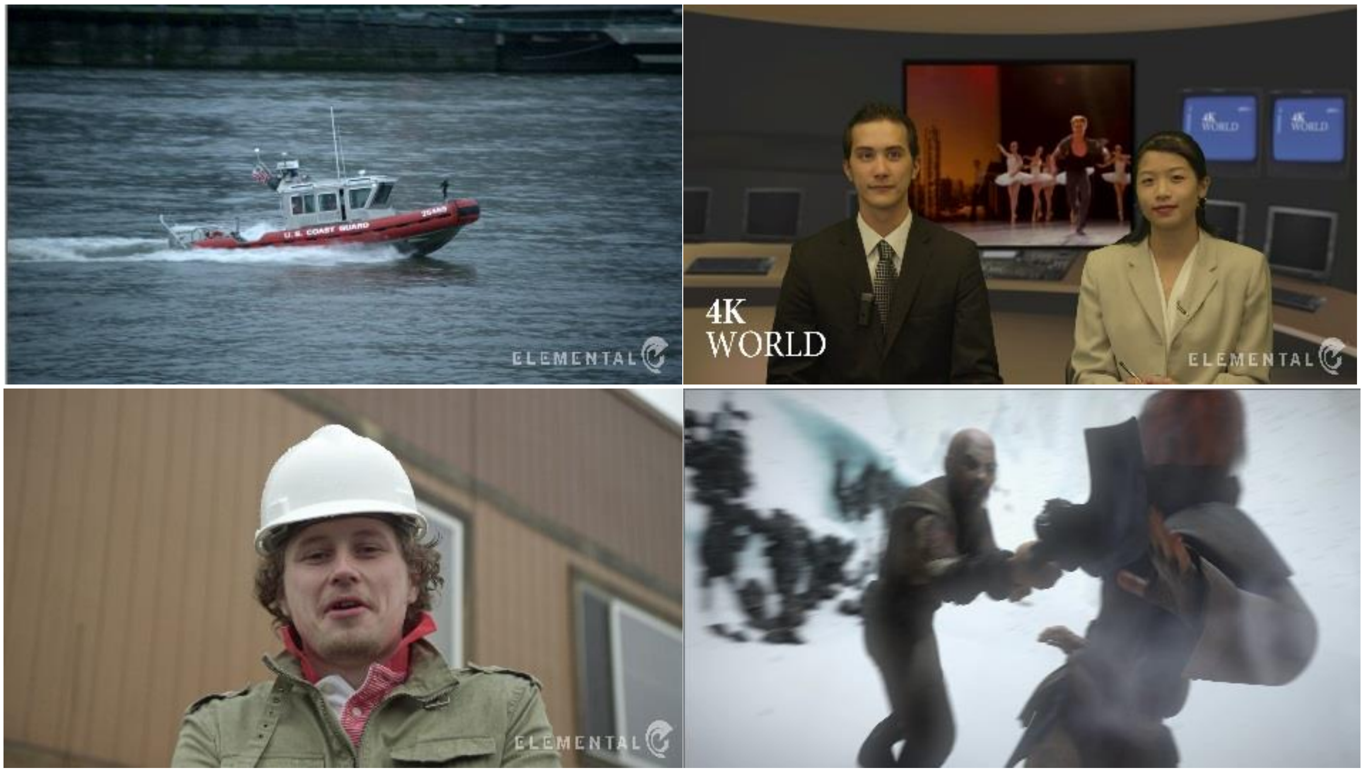

Fig. 1 One representative frame from each of the four source video sequences used in tests.

Table 2 Test video sequences content type

Video sequence	SI	TI	Motion classification
Coast	10.84	16.92	Moderate
News	17.52	21.24	Moderate
Foreman	19.71	38.29	High
Sintel	16.39	72.26	High

Table 3 Codec parameters for tests

Parameter	H.264/AVC	HEVC
Profile	High (5.1)	Main
Processing unit	Macroblock (MB)	Coding Tree Block (CTB)
Processing unit size	16×16	64×64
GoP size	40	25
GoP frame structure	IPPPP…	IBBPBBP…
Frame rate	25 fps	25 fps
CBR bitrates	20 Mbps	13.5 Mbps

3.2 Testbed configuration

The H.264/AVC and HEVC streaming experiments took place over a testbed that allowed both live and pre-stored video to be transmitted over a wireless link using broadcast standard protocols. The testbed actually also included a Wide Area Network (WAN) emulator that allowed packet loss, reordering, and duplication prior to wireless transmission. However, in these experiments the WAN part of testbed was effectively bypassed. As mentioned in the previous Section, packet framing was as an MPEG2-TS prior to UDP packetization. To achieve this, H.264/AVC or HEVC elementary streams (ESs) were converted into MPEG2-TS Packetized Elementary Stream (PES) format. That format, in general allows the subsequent multiplexing of audio, data, or other PES streams, though only video was sent in these experiments. MPEG2-TS is a two-layer packetization scheme, which splits PES packets into packets of fixed length, each 188 bytes in size with a 4-byte header. In general though, packets from different PES streams can be interleaved within a single UDP packet. Seven fixed-length packets were placed in a packet, with an 8-byte UDP header, allowing the standard Ethernet Maximum Transport Unit (MTU) size of about 1500 bytes to be approached. In the case of H.264/AVC, the FFmpeg built-in software was adopted but in the case of HEVC an enhanced version of the FFmpeg solution was constructed with LAV splitter and software [30].

The overall testbed structure is shown in Fig. 2 for HEVC stream processing. The structure consists of two stages and was designed with the open source DirectShow (DS) [35] architecture as an overlay control mechanism, thereby enabling synchronization of testbed modules, regardless of hardware differences and data transport. The DS control overlay did not create any overhead during transmission. At the sender, there was a bitstream processing stage, whereby the raw video is encoded, when encoding was performed live or in off-line pre-processing. In the streaming stage, the server-side operation performed MPEG2-TS encapsulation and transmission over UDP, while the client-side operation receives packets and performs MPEG-TS de-capsulation to produce what is in effect a distorted ES. The post-streaming stage decodes the received H.264/AVC or HEVC ES and either rendered the decoded video or saved it to file for evaluation. Except for the bit-stream processing stage, whern there is an option of inputting pre-processed video, all other modules functioned in real-time. The current evaluation experiments acted upon HEVC (and H.264/AVC) encoded bitstreams through off-line pre-processing and decoding to a YUV file for later evaluation.

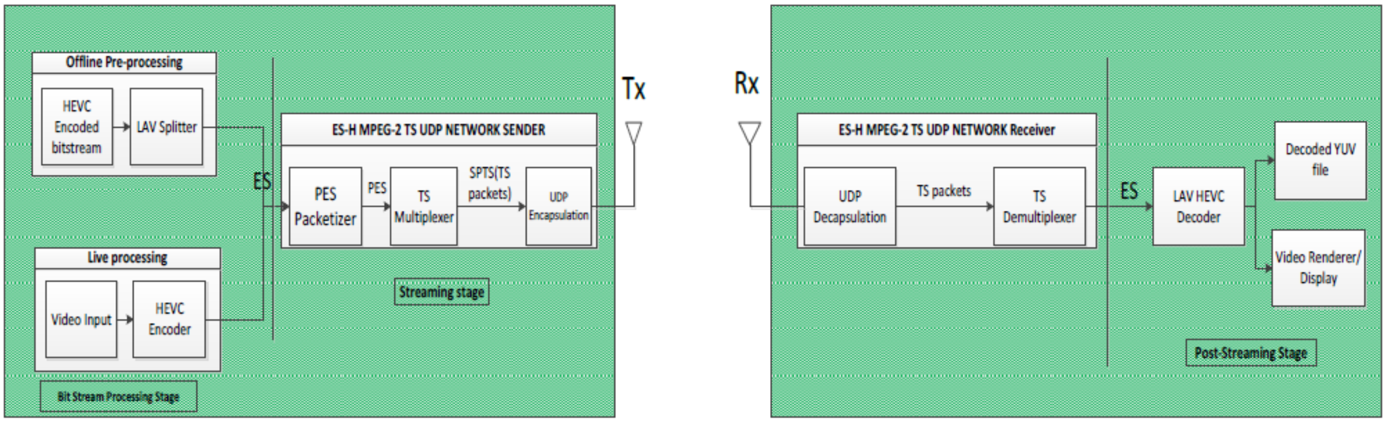

Fig. 2 Wireless testbed streaming structure.

IEEE 802.11ad 60 GHz transmission took place between a Dell Latitude 6430u laptop placed indoors at a distance of 10 m from a Dell wireless WiGig dock D5000 802.11ad access point. Specifically, the setting was within an open-plan laboratory with line-of-sight communication between sender and receiver device.

4 Findings

4.1 Video Quality

To calibrate the following tests with packet loss, error-free results are reported in Fig. 3. The findings suggest that HEVC produces marginally better quality video at a lower bitrate. In addition, higher-resolution video results in lower objective MOS ratings and lower motion videos have higher qualities. However, the data-rate was fixed whatever the resolution (refer to Table 3). This results in less compression for lower resolutions, as the Quantization Parameter (QP) varies somewhat to match the available bitrate. Moreover, the encoders have been able to take advantage of additional bitrate to improve the quality of low-motion videos. In other words, both codecs avoid simply increasing the bitrate artificially, by, for example, including more intra-coded MBs or CTBs. The relationship, which is content dependent, between bitrate and objective MOS is demonstrated in Fig. 4. It is likely that as the bitrate is increased, there will be a reduced impact from packet loss, owing to there being less information in each packet.

The video was now streamed over the IEEE 802.11ad link, as described in Section 3.2. Fig. 5 reports random packet loss of 0.1% for a selection of the video sequences. The H.264/AVC codec now (compared to Fig. 2) appears more resilient to packet loss than HEVC, resulting in higher quality ratings for H.264/AVC encoding. This finding suggests that HEVC's more efficient encoding makes the video output more sensitive to packet loss, once the relative coding gains have been allowed for by scaling the CBR bitrates. In Fig. 5, the direction in the differences in quality between the codecs is consistent, both across the different resolutions and across the different test video sequences. Therefore, though the differences in the MOS scores (derived from

SSIM) are small, mostly between 0.02 and 0.03, they are consistent. In the case of 4K UHD resolution, the differences in MOS scores are somewhat higher. This might be because, broadly, each packet loss for HEVC leads to the loss of a larger picture area relative to H.264/AVC. Then going between the resolutions, from 480p to 720p and from 720p to 1080p, the total number of pixels increases by factors of 2.66 and 2.25 respectively. However, going from 1080p to 4K UHD, the total number of pixels increases by a factor of 4.00. Thus, broadly, the total number of pixels affected per packet may be relatively larger for 4K UHD video, though it is difficult to be sure of that due to non-linear codec behavior.

Packet loss also serves to exaggerate the difference in video quality already starting to show in Fig. 3 between lower (higher quality) and higher resolution (lower quality). Similarly, when packet losses occur, even at a low loss rate of 0.1%, higher motion sequences (refer to Table 2) such as Sintel suffer in quality much more than lower motion sequences such as Coast. Again a possible explanation, when a fixed rate CBR is involved, is that lower spatial resolution and lower motion video sequences will tend to be less compressed. Consequently, with more coded content per packet for lower resolution and lower motion videos, error concealment is better able to reconstruct missing packets. The effect upon 4K UHD videos with more motion is to depress their relative video quality as the PLR percentages increase, as they do in Fig. 6. In contrast, Coast particularly gains in its quality ranking owing to its relatively low motion (refer to Table 2). Without protection all video sequences tested have poor to unacceptable video quality beyond a PLR of 0.6.

Though it is not the main focus of the current paper, it is clear that thought needs to be given as to how to protect HEVC video in a high packet loss conditions. Unlike, H.264/AVC, which has multiple error-resilience features [61], HEVC appears comparatively light in that respect [56] in order to reduce the overall complexity. As previously mentioned in Section 3.1, purchasing an implementation such as that of [15] might be one solution, while others may prefer a bespoke solution, possibly involving error concealment (refer to Section 4.3). Flexible Macroblock Ordering (FMO) was a feature of H.264/AVC that lent itself to various error-resilience purposes, such as, with the FMO checkerboard pattern sending one slice of ‘black’ macroblocks separately to a slice containing ‘white’ macroblocks, as if one slice were to be lost then the other could be employed to reconstruct it. However, FMO added complexity to H.264/AVC and was not widely implemented. Alternatively, HEVC introduced, possibly variable-sized, tiles as an aid to parallel processing and these tiles could also serve in error resilience. For example, they could be used for tile duplication during transmission, as slice duplication was an error resilience feature of H.264/AVC. They might also serve to give extra error-coding protection to more important regions-of-interest.

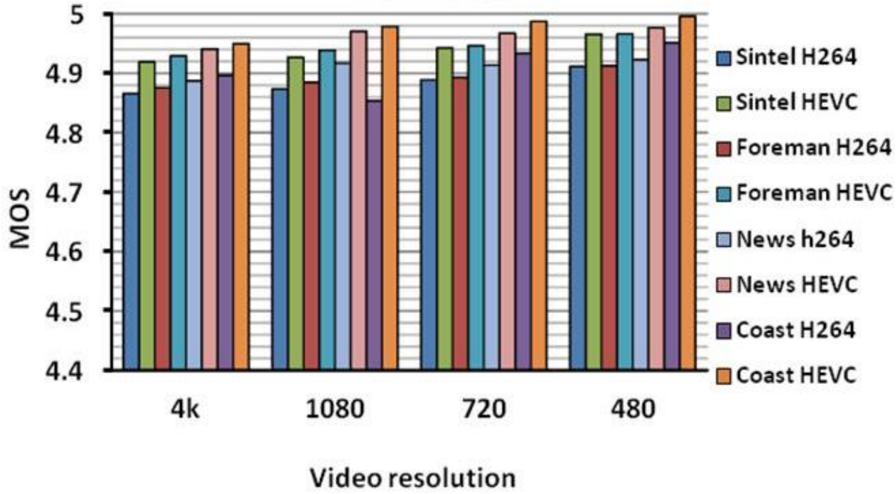

Fig. 3 Objective MOS video quality assessment for a range of resolutions and either H.264/AVC or HEVC codec, showing improved MOS for HEVC when there are no packet losses. Notice the truncated vertical scale.

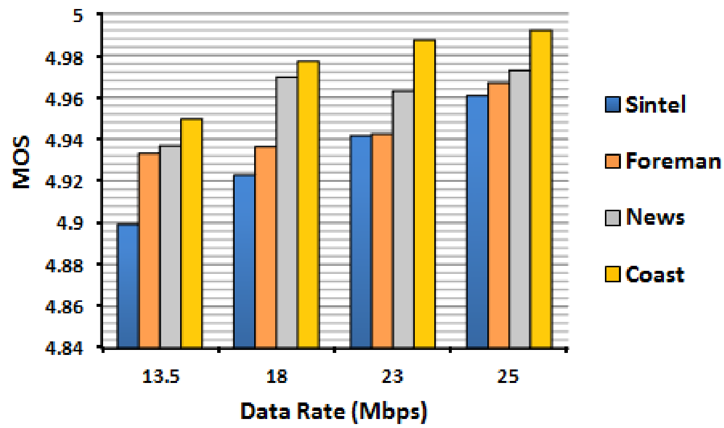

Fig. 4 Objective MOS video quality assessment for a range of data-rates with 4K UHD resolution, and encoding with the HEVC codec when there are no packet losses. Notice the truncated vertical scale.

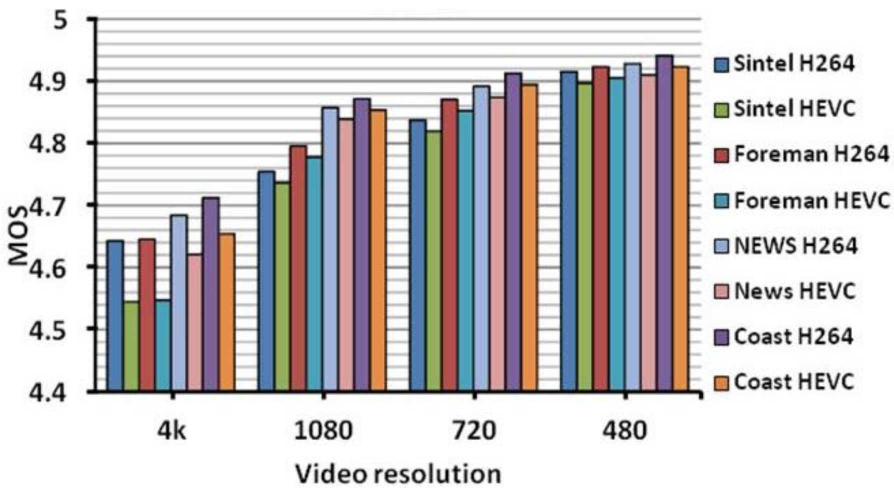

Fig. 5 Objective MOS video quality assessment for a range of resolutions with PLR = 0.1% and either H.264/AVC or HEVC codec, showing improved MOS for the older codec even when there are limited packet losses. Notice the truncated vertical scale.

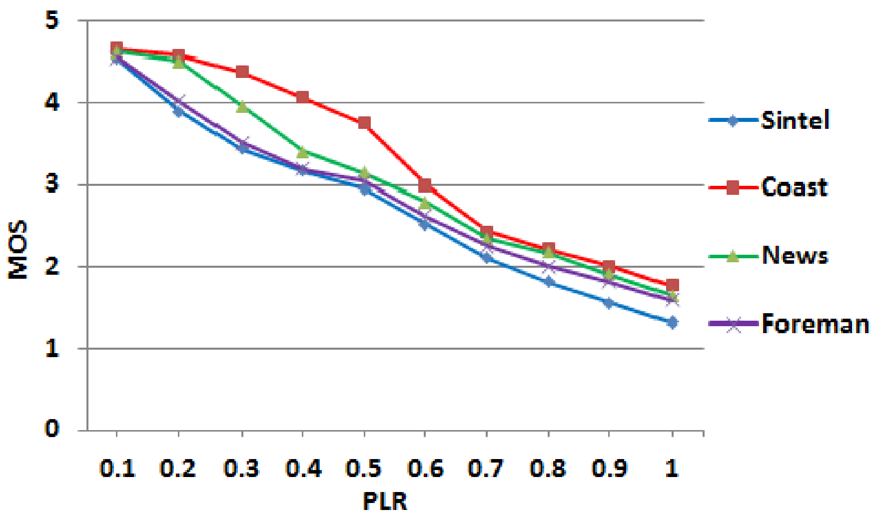

Fig. 6 Objective MOS video quality assessment for a range of PLR percentages with HEVC codec encoding and 4K UHD resolution.

4.2 HEVC streaming

In this Section, the HEVC video configuration was similar to that for the same video sequences as in the previous Section. However, the target CBR bitrate was incrementally increased, so that the reader can judge to what extent an increased available bandwidth allows HEVC to improve upon video quality in the presence of some packet loss. The PLRs were measured at approximately 0.1% during IEEE 802.11ad streaming, with video quality now directly reported as SSIM. Fig. 7 records the results from these tests, including standard error bars (one standard deviation of the mean).

It is evident that as the compressed bitrate is increased, the relative impact of packet losses appears to decrease. This effect can be assigned to the quantity of coded video data that is distributed among packets, each of the same size, with the exception of the last packet. The PLR remained approximately the same, 0.1%, as a result of the measured stable wireless channel conditions during the experiments. This implies that, in fact, larger packets did not lead to increased PLR, as might have been thought [25]. At a CBR rate of 13.5 Mbps, for the same video sequence, there will be fewer packets compared to compressing and sending the same clip at 25 Mbps stream. As a result the distribution of compressed data over more packets in the case of a 25 Mbps stream decreases packet loss sensitivity. In other words, a similar effect takes place to that which was previously highlighted when going from HEVC to H.264/AVC compression. In practical terms, it is generally preferable, despite HEVC’s efficient coding efficiency, to select as high a compression rate/bitrate as possible, especially in respect to high bandwidth 60 GHz transmission.

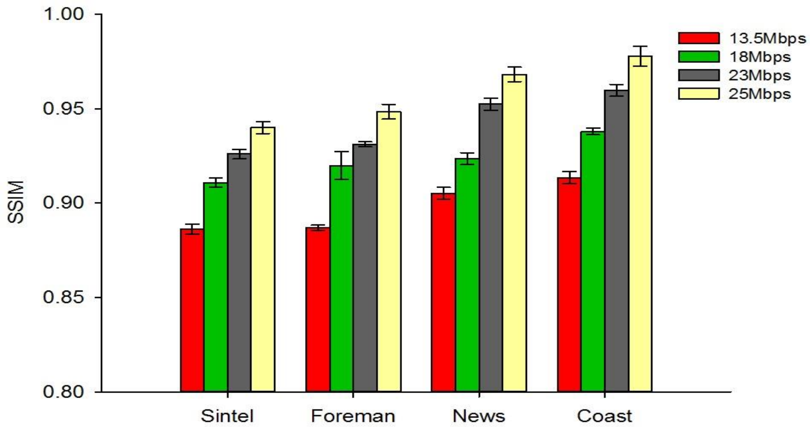

Fig. 7 Video quality after transmission over IEEE 802.11ad link for 4K UHD video compressed by HEVC at various bitrates (PLR approx. 0.1). Notice the truncated vertical scale.

4.3 HEVC error concealment

Improved error concealment may well be necessary for some applications aimed at portable devices. For example, a further codec comparison study [43] reached similar findings to the current paper for packet loss rates of 1%, 3% and 5%, though for video clips of HD resolution or below, not UHD. As in this paper's study, a basic level of error concealment, slice/frame copying was set. However, the authors of [43] concluded that this form of error concealment was only sufficient for scenes with limited motion and mentioned the "necessity" for developing advanced error protection in the case of HEVC. Two issues may arise when developing an error concealment method. Firstly, if something other than previous slice/frame replacement is employed, what can be chosen as a replacement? For example, for scalable HEVC, in [54], four different replacement sources could be chosen from. However, signalling of a pre-determined choice made by the encoder was required, which will require signal protection. Secondly, rate-distortion modelling for rate control, e.g. [18] [33], tends to only include in its modelling the impact of slice-copy error concealment and does not model other forms of error concealment, such as motion-vector estimation. Thus, varying the error concealment method has an impact on rate control unless allowance is made. For example, in [26] the impact of errors was modelled in terms of the quantization distortion in the current block, the error propagation from previous blocks, and the error concealment impact for future blocks. However, the resolution of the test videos in [26] was only CIF and the computational impact is unreported. Unfortunately, as was pointed out in [11], the motion-vector estimation methods, as well as other error concealment techniques, that were proposed for H.264/AVC, do not directly transfer to HEVC. This is because those methods and techniques assumed small blocks, whereas HEVC no longer employs MBs but Coding Units (refer back to Table 1), of which the largest can be sixteen times larger than H.264's 16 × 16 MBs. Thus in [11], a method of motion vector estimation from CUs discards unreliable CU MVs and merges other MVs. The authors note that simple motion copy error concealment in their tests is worse than the error concealment used in the current paper, whereas a more complex form of motion copy gives a maximum per frame improvement of 1.3 dB over previous frame concealment. However, blockiness as a result of this form of HEVC error concealment is still reported. Therefore, in [23] downhill Simplex optimization was applied at block boundaries to reduce blockiness and the computational overhead of the search, though it remains to be seen, as the computational overhead is unreported in [23], whether such a method is suitable for portable devices and that it is possible to avoid local minimums. Other forms of error concealment are reviewed in [23] but it is apparent from the discussion of HEVC motion copy concealment that the development of sufficient methods is complex and may face issues of computational overhead on portable devices with constrained battery consumption.

4.4 Discussion

At the time of writing, standardisation of UHD-Digital Video Broadcasting (DVB) is ongoing to allow 4K UHD video to be broadcast in a cost-effective manner. Currently, there are practical impediments [19] in terms of available content (with some content needing to be up-scaled from HD format); available bandwidth with the 12 GHz band being a possibility in the medium term and 22 GHz band in the long term for satellite transmission; and sufficient compression/modulation to sufficiently reduce the bitrate to fit the channel, especially if frame rates were to double from the current 50 or 60 Hz. If there was an increase in the color gamut, necessitating an increase from 8 to 10 bits, then the bitrate could increase further by 25%. Therefore, any cost model for moving from HD to 4K UHD probably needs to await the outcome of the standardisation process because decisions made about satellite broadcasting will have an impact on mobile delivery of 4K UHD, for example in terms of the available content. The research in [45] showed that the form of modulation had an impact in reducing the cost of satellite broadcasting of HD relative to UHD video transmission. Thus, a simulation indicated a 7% increase in cost if Quadrature Phase-Shift Keying (QPSK) 5/8 modulation was used compared to a 0% increase if 8PSK modulation was employed for UHD, as opposed to HD transmission. The simulation's results were dependent on: the codec tested (HEVC); bit depth expected, 8-bits; the noise model applied (Rician with k = 5 plus Additive Gaussian White Noise (AWGN)); and the desired bit-error rate, 3×10^{-5}, using DVB-Satellite second generation (S2) 'direct-to-the-home' satellite settings, with and without channel estimation. Notice that in [66] the dependence on modulation scheme and modelled noise for 60 GHz wireless channels was investigated, also showing that higher forms of modulation led to a significant gain in channel capacity. In 2001, the Federal Communications Commission (FCC) reserved 7 GHz of bandwidth in the range 57 to 60 GHz (available as unlicensed bandwidth in many countries and regions likely to have 60 GHz transmission) but also limited the transmission power to 40 dBm for an antenna of 0 dBi gain. The latter restriction means that, in internal environments, there is about a 20 dB attenuation at distances up to 20 m (in a conference room) for line-of-sight (LOS) transmission but a much higher rate of attenuation for non-line-of-sight (NLOS) transmission. Capacity was found to be about 3.75 Gbps for simple Binary Phase-Shift Keying (BPSK) modulation and no fading, while this capacity dropped to 2.9 Gbps for Rayleigh fading channels, for a 5 GHz channel.

5 Conclusion

This paper’s main finding is that for contemporary portable devices, capable of capturing and wirelessly streaming 4K UHD, the H.264/AVC codec still has a role whenever packet loss is a threat. Even though there is an increase in bitrate from using H.264/AVC, the overhead from channel coding to protect HEVC streams may balance that. In fact, high throughput wireless transmission through IEEE 802.11ad at 60 GHz means that bandwidth is at less of a premium for higher resolution compressed video transmission. When IEEE 802.11ay is eventually released, as a follow-up at 60 GHz to IEEE 802.11ad but with the amalgamation of four of IEEE 802.11ad channels, the bandwidth will become even less of a premium. Results show that it may be preferable to employ lower compression rates (higher bitrates) in those circumstances. This counter intuitive suggestion, applies both when choosing a less efficient codec and when selecting a higher data-rate for transmission over error-prone channels. In practical network conditions, it could be that H.264/AVC may sometimes be preferred for video streaming, even when the available bitrate is the same as could be used by HEVC. To accomplish the lower bitrate offered by HEVC requires greater consumption of a portable device’s resources, which might lead to more frequent recharging, an irritant to the consumer. The paper indicates that at higher PLRs it may be necessary to either introduce error coding, the overhead of which will eat into the compression efficiency of HEVC, or error-resilience measures, some of which are not natively available in HEVC and when provisioned may add to the cost of an implementation. Recognizing this situation, progress has been made towards improving error concealment for HEVC transmission in error-prone channels outside the video standard. Due to the move away from MBs in HEVC, error concealment methods that previously worked for those small blocks may be unreliable for the sometimes large coding units of HEVC. In the case of motion vector estimation for motion copy error concealment, the choice of adjacent motion vectors has to be refined and the risk of introducing blockiness needs to be mitigated. Nevertheless, such methods represent the future for high-quality wireless video transmission, if the error concealment algorithms are not too demanding upon portable devices.

CBR encoding was used in the above experiments, allowing convenient comparison of results, aside from the benefits from CBR for transmission bandwidth and storage planning. In practice, for live streaming, Constant Rate Factor (CRF), a modified version of CBR with a soft target bitrate, with a Video Buffer Verifier (VRF) limit may be preferable for streaming, as it avoids an encoder targeting a bitrate regardless of coding needs. For live streaming in the tests, one-pass encoding was chosen to reduce latency. Two-pass encoding can be configured in the open-source x265 codec implementation of HEVC and for Video-on-Demand applications that allows file storage limits to be accurately met. The video quality gain from two-pass encoding relative to the extra latency involved in gathering content statistics in a first pass are a subject for further research.

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