Innovations in Video Error Resilience and Concealment

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Abstract: Router buffer overflow and random bit errors have always been a problem in the Internet. The growth in multimedia applications in mobile extensions of the Internet has increased the threat from error bursts, random errors, and packet erasures that are a manifestation of wireless channels. Source-coded error resilience has come to prominence in the H.264/AVC codec standard, and this paper reviews such innovations surrounding this codec. Some innovations are new variants of an existing technique such as data-partitioning and some are entirely new such as the powerful dispersed-mode flexible macroblock ordering. Other techniques, such as reversible variable length coding, were not be transferred to H.264 from earlier codecs and, hence, innovations are proposed to still provide robust entropy coding. Other variants such as adaptive intra-refresh are still being experimented with. When error resilience or other protection methods fail to present an adequate video frame then error concealment can be brought to bear. This paper reviews error concealment which is important to commercial companies as they are able to distinguish their codec from others. The paper considers spatial, temporal and hybrid error concealment methods. Though this paper contains over one hundred references it can only provide a slice through this rich field.

Keywords: Data-partitioning, error concealment, error resilience, FMO, intra-refresh, multiple reference frames, picture slices, redundant pictures, robust entropy coding, RVLC, video services

1. INTRODUCTION

With the prevalence of video services for mobile networks [1] has come an increased need to protect fragile compressed video streams against the endemic noise and interference that are the defining characteristic of wireless networks. Unfortunately, as the basis of video compression [2] is mainly[1] (though not exclusively) the exploitation of temporal redundancy, there are considerable between-picture[2] data dependencies embedded in the packets sent to a mobile device. A further weakness is the sequential nature of entropy coding, which results in within-picture data dependencies. One way to protect a video bitstream is through error resilience and as a back-up measure at the decoder, error concealment can be applied. However, error concealment is not a complete solution, merely representing a means of repairing any damage if other methods have failed.

These forms of protection are mainly concerned with networked transport of video, especially across error-prone wireless networks [3]. The main forms of video services that can benefit are: circuit-switched or packet-switched conversational services, such as video telephony or video conferencing; and live or pre-recorded video packet-switched streaming. Because reliable transport, typically through TCP, can be employed, multimedia messaging or video download is less likely to benefit from error resilience or concealment.

Channel coding is beyond the scope of this paper (refer to [4] for a summary of channel coding for video) and indeed Shannon's source-channel coding theorem states [5] that 'lossy' compression schemes can be developed separately from channel coding schemes. However, when stringent delay and computational complexity constraints exist, joint source-channel coding [6] should be considered.

1 Notice also that hybrid video codecs exploit to some degree other forms of redundancy such as spatial, psychovisual, and statistical.

2 In this paper, the terms video 'picture' and 'frame' are used interchangeably and progressive video is normally assumed.

Video services are known as loss-tolerant. However, this generalization is misleading, as the loss of more than 10% of packets will generally lead to a severe deterioration in the video quality. The most likely cause of packet loss in wired networks is through buffer overflow as a result of traffic congestion in ‘best-effort’ IP networks. However, wired networks also experience some random bit errors caused by impulse noise, which result in bit inversion, insertion, and deletion. Wireless networks are more likely to suffer from random bit errors due to radio frequency noise in transceivers. Because of the sequential nature of entropy encoding, a single bit error can propagate until the decoder is re-synchronized. However, in the Context-Adaptive Binary Arithmetic Coding (CABAC) used in state-of-the-art coders, errors are difficult to identify immediately they occur [7]. Context-Adaptive Variable Length Coding (CAVLC) does not suffer from this problem and because of its lower computational overhead is recommended for mobile devices.

Error bursts can occur through the imperfections of a storage medium or through a deep fade, when a mobile device enters an adverse wireless environment. Though there is a debate on the issue, it is generally agreed [8] that error bursts are more damaging to video quality within a frame than random errors. Such errors can not only spread temporally through a sequence but can also extend spatially, through the mechanism of motion-compensated prediction. Complete packets can be dropped in a wired network through buffer overflow and additionally in a wireless network if the signal strength drops below a threshold.

The H.264/AVC (Advanced Video Coding) standard [9] forms the basis of innovations in error resilience [10], as well as incorporating many existing techniques [11] from previous codecs. These techniques have at their core the ability to encode pictures into self-contained sub-units called slices [10]. Each slice resynchronizes the entropy decoder, thus limiting the scope of error propagation to within a slice. However, slicing comes at a cost in terms of the additional bitrate needed for internal headers.

To prevent temporal error propagation across a video sequence, intra-coded macroblocks (MBs) [2] can be used to refresh damaged areas. Besides periodic intra-refresh, which is most suitable for broadcast video, there are other intra-refresh patterns [12] more suitable for wireless networks, as they do not result in sudden increases in the data-rate and as they can provide gradual decoder refresh (GDR). Moreover, periodic intra-refresh can cause unnecessary delays, which again are a threat to low-delay applications such as video telephony. In fact, though intra coding is generally faster than inter coding to compute, because of coding inefficiency, the number of packets produced in an intra-coded picture considerably exceeds that of an inter-coded picture [2]. The result is that the excess packets occupy the send buffer causing delay.

On the other hand, an H.264/AVC codec can use up to sixteen previously-coded frames as references [13] for the current frame being encoded. This not only increases the compression efficiency but also the inter-frame dependency.

When transmission errors do occur, pixels, represented in the packetized bit-stream, cannot be decoded and are replaced by concealed versions of previously-received pixels [14], often aided by the presence of error-resilience coding. In particular, Flexible Macroblock Ordering (FMO) [15] in dispersed mode aids the reconstruction of missing macroblocks (MBs) through interpolation from surrounding MBs. Thus, error-resilience methods go hand-in-hand with error concealment. However, unlike error resilience, error concealment is a non-normative feature of H.264/AVC [16] in the sense that its form is not specified in the standard but left to implementers. Many error concealment methods have been proposed [17] but there is an issue arising from their computational complexity.

Section 2 of the paper now considers how best to protect video services in error-prone transmission channels.

2. PROTECTION ALTERNATIVES

This Section briefly discusses protection alternatives that have been explored over time, with Table 1 presenting a summary of the alternatives.

2.1 Forward error correction

Most wireless technologies provide physical-layer forward error correction (FEC). However, such corrections are limited in the extent of the errors that can be corrected as otherwise the FEC overhead becomes intolerable. However, additional packet-level application-layer (AP)-FEC is still recommended [18] for multicast and broadcast services over wireless cellular networks. This recommendation arises from the disruption that can occur to IPTV services [18] from the loss of even a small percentage of packets. Consequently, the DVB, 3GPP, ATIS and ITU FG include erasure codes in their standards for download and streaming video services. AP-FEC is generally aimed at packet erasures, when a packet is either lost or received. If the video is first sent over a managed wired network or during benign channel conditions then AP-FEC is a burden. However, also notice [18] that burst errors leading to a packet being declared lost are a problem in Asymmetric Digital Subscriber Link (ADSL).

2.2 Error control through ARQ

Error control through one of the varieties of Automatic Repeat request (ARQ) [19] is possible. However, ARQ is unsuitable for interactive or conversational video services such as video conferencing because of the delay introduced. Besides simple ARQ and even hybrid ARQ (e.g. for IEEE 802.16e [20]) are or may be already available at the datalink layer.

2.1 Packet interleaving

End-to-end latency constraints are the key restriction. For example, Internet Protocol TV (IPTV) standards recommend [21] no more than 50 ms for the complete network path. For that reason packet-interleaving at the application layer [22] may result in an unacceptable packet delay leading to buffer underflow, if not properly regulated. Data interleaving can also occur [23] as a way of countering error bursts and random errors within entropy-encoded data. Such a form of interleaving is Error-resilient Entropy Coding (EREC) [23] which was applied to the H.263 codec form of data portioning.

2.3 Alteranative error resilience techniques

Error-resilience techniques are a way of responding to 'lossy' wireless channels at the video codec level. These methods may impose a limited burden, particularly if an appropriate form is chosen such as data-partitioning [24] [25]. In the H.264/AVC codec form of data-partitioning, higher-priority data are effectively assigned to different packets (though the H.264/AVC standard does not actually specify such an assignment). Error resilience methods prior to 2000 are reviewed in [11] [26] and [27].

Application-layer framing (ALF) [28] works in conjunction with error resilience to avoid unsuitable packetization decisions for the target network for transmission. As an example, in an H.264/AVC codec, it is important not to break-up slices into separate network packets as this could lead to the breakdown of decoder synchronization. It is possible to include other categories of error resilient coding such as error resilient prediction [29] [30], layered coding [31] [32] [33] and multiple description coding [34] [35] [36]. These topics deserve an additional paper and, hence, are declared out of scope for this paper.

2.4 Combined error protection approaches

A combination of the aforementioned methods is preferable as part of an error response strategy and unequal error protection (UEP) is possible. In UEP, protection is prioritized according to compressed video content or the structure of the video. Acknowledgments are possible but their impact on delay must always be judged. For example, in [37] layered streaming was attempted across an ad hoc network in which multi-hop routing and broken links can lead to high levels of delay. In layered streaming [37], a more important base layer allows a basic reconstruction of the video while one or more enhancement layers can improve the quality. Because of the high risk of delay, in [37] it was only possible to send one ACK at most to secure the base layer.

Table 1. Video protection alternatives.

Protection	*Usage*	*Remarks*
Joint source-channel coding [6]	Real-time video services with stringent delay and computation constraints	Optimizes the source coding rate –distortion according to the given channel conditions
Application layer FEC [18]	Erasure coding for MBMS 3G wireless service [21]	Current usage is not adaptive but Raptor coding brings reduction in computational complexity May replicate PHY layer protection
Error control [19]	Hybrid ARQ types 1 and 2 Low bit-rate video	Latency issues arise May replicate data-link layer protection
Packet inter-leaving [21]	Protection against error bursts from deep fades	Unsuitable for conversational video services, such as teleconferencing and videophone
Error resiliency [29]	Encoder-based protection of video streaming	End-to-end solution, often with limited overhead
Error concealment [14]	Helps reconstruct at the decoder	Non-normative feature of H.264/AVC Can be computationally demanding

2.5 Content dependency

Another dimension to the problem space is the relationship between content type and the effectiveness of protection. Content type chiefly manifests itself in source-coding complexity, either spatial or temporal complexity, both resulting in reduced coding efficiency but with temporally complex content more at risk from temporal error propagation. In an implementation, an encoder may choose intra-coded MBs when the motion disparity between frames is large. However, if such intra-coded MBs are lost in transmission then error concealment will be less effective, resulting in a drop in video quality and a continued risk of temporal error propagation. Besides, including intra-coded MBs usually results in a drop in coding efficiency and, hence, for broadcast Constant Bit Rate (CBR) video a drop in overall video quality.

Finally, it would create a misleading impression to suggest that there is one single error resilience method that will suffice. In fact, an appropriate error resilience strategy [38] combining several techniques can be chosen.

The paper now specializes in Section 3 to consider the many innovations in error resilience that have followed on from the arrival of the H.264/AVC codec. A selection of patents is considered in Section 4, before turning to error concealment. In Section 5 the main areas of development are identified and some patents relevant to these areas are commented upon. The paper is completed in Section 6.

3. ERROR RESILIENCE INNOVATIONS

3.1 Contribution of H.264

The H.264/AVC standard introduced a range of error resilience techniques or tools [39] [40] and no review of recent innovations would be complete without starting by examining the H.264/AVC standard's contribution. H.264/AVC codec conceptually separates, Fig. 1, the Video Coding Layer (VCL) from the Network Abstraction Layer (NAL). The VCL specifies the core compression features, while the NAL supports delivery over various types of network. This feature of the standard enables easier packetization for the purposes of ALF. The NAL facilitates the delivery of the H.264/AVC VCL data to the underlying transport layers such as the RTP/UDP/IP, H.32x, and MPEG-2 transport system.

A NAL unit contains a single slice (isolated coding region), a data partition, or side information. In the simplest form of packetization a NAL unit is placed with a single Real Time Protocol (RTP) headed packet, if the codec is operating in RTP mode. This paper assumes RTP/UDP/IP packetization with Real-Time Protocol (RTP) headers providing sequence numbers and timings information [41]. Other protocols are suitable for the multiplexing of video, audio and control data, as well as multiple TV channels. Some examples are given

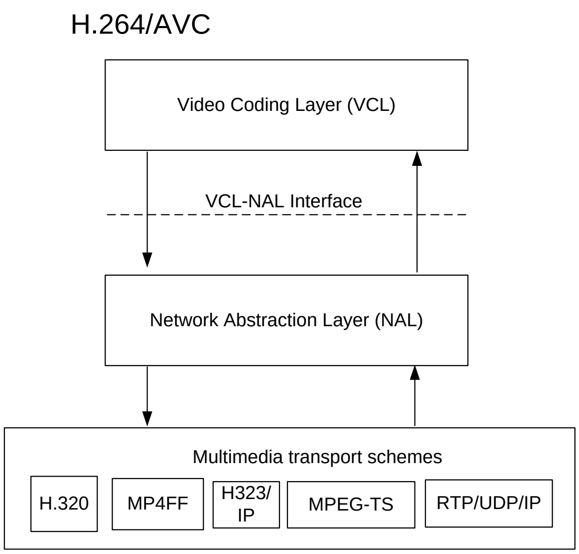

Fig. (1). H.264/AVC VCL and NAL organization.

in Fig. 1 and their characteristics are summarized in [11]. For interactive applications such as videophone, H.223's mobile extensions provide five levels of protection for the multiplexer and its overhead. As the level of protection increases, the synchronization flag size grows along with header protection. Error burst lengths of up to 16 bits are assumed [42], with bit error rates of between 10-5 and 10-3. Packet sizes can be of variable length but are generally confined to 100 Bytes. If the protocol structure of H.223 is affected then packet erasures are declared.

3.1 Header error resilience

Table 2, which should be referred to in the subsequent discussion, is a summary of resilience methods for headers and entropy encoding. Protection of important header data is vital as was recognized in the MPEG-4 predecessor through Header Extension Code (HEC) [43]. This is one bit, which when set informs the decoder that resynchronization information is repeated in the video packet, thus allowing decoding to commence even if the initial video object plane header is corrupted. It is worth mentioning that MPEG-4 also allows the duplication of motion vectors (MVs) [44], which in H.264/AVC appears to require duplication of data-partition A (DP-A) (when used, as discussed later).

H.264/AVC does permit out-of-band reliable transport of header data in the form of parameter sets [45], which can either contain information that will not change throughout a sequence or a coded picture. Indexes to stored information are sent in parameter sets, thus reducing the data sent. Supplemental Enhancement Information (SEI) and Visual Usability Information (VUI) messages (contained in NAL units) provide ways of including additional side information into an H.264 bitstream. For example, in the Scalable Video Coding (SVC) extension to H.264, SEI messages have been used [46] to indicate the presence (or discard) of redundant slices to protect key pictures. Other uses are to indicate error concealment distortion information and regions of interest (ROIs). Because SEI NAL units are likely to be small, a NAL unit aggregation scheme has proved effective for H.264/AVC [47].

An H.264/AVC slice header contains information vital for the decoder and, hence, its corruption can again cause loss of decoder synchronization. CAVLC entropy encoding allows easier detection of errors and in [7] this facility was used to attempt to reconstruct corrupted slice headers. The technique was based on the commonality between some parameters for all slices within a Video Coding Unit (VCU).

3.2 Protection for entropy coding

In H.264/AVC, adaptive entropy encoding is by arithmetic coding or universal variable length coding. Either way, as previously mentioned, a single bit error in the compressed stream is capable of disrupting the variable length decoder (VLD). VLD resynchronization markers can be inserted [11] [47] at regular intervals and in earlier codecs (MPEG-1/2, H.261/3) they were inserted after a fixed number of motion estimation blocks but a variable number of bits (called a Group of Blocks). Because this practice increases the probability of error, an alternative is to insert after a fixed number of bits but a variable number of blocks. In H.264/AVC, there are no restrictions on slice length which allows some customization in that direction. It also allows slice length to be constrained to within the Maximum Transport Unit of the network, which is an important protection provision.

Assuming a slice per NAL unit, it is still possible for a NAL unit to be fragmented, which can potentially cause synchronization problems. The most likely cause of fragmentation arises from slices of super high resolution or high fidelity video [48]. However, as optical networks are used for this application the bit error rate is also likely to be very low.

In previous codecs (H.263 and MPEG-4), Reversible Variable Length Coding (RVLC) [49] was employed. In the event of a synchronization error, RVLC allows the entropy coder to decode from either end of a slice. In [50], it was shown that the RVLC scheme employed for MPEG-4 was not the best in terms of error resiliency judged by the potential length of spatial error propagation. Because separate codebooks are employed for the different categories of compressed information (MVs and transform coefficients) data-partitioning should be in place.

In H.264/AVC each data-partition occupies its own NAL unit with some cost in header overhead. However, notice that header compression [51] usually reduces the 40 B of the RTP/UDP/IP combination to an average of 2 B. In H.263 and MPEG-4 data partitioning, when selected, occurs within a single packet and only markers separate the partitions. However, in these codecs RVLC incurs an overhead of from 1-2% [44] due to the need to select reversible codes.

Another technique for robust entropy coding is bidirectional reversible bitstreams [52]. In this technique, each VLC codeword is reversed to form a reversed VLC bitstream. Subsequently the entire reversed bitstream is delayed and XORed with the original bitstream. The delay or shift must be greater than or equal to the maximum-sized VLC codeword. Decoding in the forward direction takes place by decoding each symbol in turn. Then a reversed version of the decoded symbol is XORed with the composite bitstream to recover an offset symbol. The recovered offset symbols can now be decoded. The process can also work in reverse, starting with the last symbols. This scheme still requires data partitioning to be applied to separate out the different types of data.

Unfortunately, bidirectional reversible bitstreams [52] will not work in H.264/AVC because CABAC requires the symbols to be decoded in the same order they were encoded. However, it has been recently proposed [53] that instead of reversing each symbol, entire MBs are reversed. Again an offset of the longest MB length is chosen to ensure the first or last MB is separately decodable. In this way, slices can be decoded from either direction and, in fact, they are simultaneously decoded in both directions. This procedure allows a similarity check to be performed as a method of error detection. The scheme [53] also proposes a post-processing technique along with error concealment to further aid recovery.

Table 2. Header and entropy coding resilience

Technique	*Usage*	*Remarks*
	Header protection	
Parameter sets [45]	Robust header transport using out-of-band (e.g. session control protocol) transmission	Vital header info. is protected, compare MPEG-4 HEC
SEI messages [46]	In-line notification of bitstream configuration, e.g. redundant picture frequency	Could be adapted for error resiliency
	Entropy coding protection	
Slice resync. markers [47]	Robust entropy encoding	Potential for long and frequent markers, though standard practice
RVLC (not in H.264/AVC) [49]	Robust entropy encoding, limited reduction in coding efficiency	Within slice resilience only
Bidirectional bitstream reversal [52]	Could be applied to H.264/AVC [53]	Introduces latency into processing

HEC = Header Extension Code, RVLC = Reverse Variable Length Coding

3.3 Frame-level resilience.

The simplest form of frame-level error resilience is through slicing. Compressed picture data is often split into a number of slices each consisting of a set of MBs. As introduced in Section 3.1, decoder resynchronization markers at the start of each slice delineate the boundaries of slices. In the MPEG-2 codec, slices could only be constructed from a single row of MBs. Later codecs such as H.261 relaxed this requirement [2], allowing contiguous MBs to form a slice. In H.264/AVC, Arbitrary Slice Ordering (ASO) allows the decoder to reconstruct a picture if the slices arrive in a different order to the encoding order. This permits the processing of MBs to start immediately, thus benefitting interactive video services. However, significant complexity arises at the decoder [54] if ASO is allowed across picture boundaries. Picture-constrained ASO still increases the complexity of FMO decoding. There are also implications for memory consumption from decoder buffering. Because of this the design of decoders has been subject to patent activity such as [55] [56].

In the video bitstream some syntax elements are more important than the others and, thus, the error robustness can be enhanced by separating these data from one another and protecting them unequally based on their importance [57]. Data partitioning in H.264/AVC [25] separates the compressed bitstream into: A) configuration data and motion vectors; B) intra-coded transform coefficients; and C) inter-coded coefficients. The arrangement allows a frame to be reconstructed even if the inter-coded MBs in partition C are lost, provided that the motion vectors in partition-A survive. Partition-A is normally strongly FEC-protected at the application layer or physical layer protection may be provided such as the hierarchical modulation scheme in [58] for broadcast TV. In order to decode partition-B and -C, the decoder must know the location from which each MB was predicted, which implies that partitions-B and -C cannot be reconstructed if partition-A is lost. Though partition-A is independent of partitions-B and -C, Constrained Intra Prediction (CIP) should be set [59] to make partition-B independent of partition-C. By setting this option, partition-B MBs are no longer predicted from neighboring inter-coded MBs, the prediction residuals of which reside in partition-C. However, there is some loss of compression efficiency if CIP is turned on. Because of the profile structuring of H.264/AVC [59], partition-C cannot normally be made independent of partition-B.

FMO [15] [39] is the principle slice-oriented technique in H.264/AVC, allowing different arrangements of MBs in a slice by utilizing the concept of slice groups. The MBs may be arranged in a slice in a different order to that of the scan order, enhancing the error resilience. In each slice group, the MBs are arranged according to an MB to slice group map. In H.264/AVC, by varying the way in which the MBs are assigned to a slice (or rather group of slices), FMO gives a way of reconstructing a frame even if one or more slices are lost.

Within a frame up to eight slice groups are possible. H.264/AVC provides different MB classification patterns. Assignment of MBs to a slice group can be general (type 6) but the other six types pre-define an assignment formula. The latter reduces the coding overhead from providing a full assignment map. Pre-defined types are [60]: interleaved, checkerboard (or dispersed), foreground, box out, raster scan and wipe. The general slice group was used [61] to form a spiral pattern of MB assignment to slice. This allowed a better scattering of errors, which in turn aided error concealment by maximising the number of recovered MBs around corrupted MBs. If this spiral pattern is not used then dispersed mode FMO can be used, as, of the pre-set types, it is the only one that allows interpolation from neighboring MBs in order to conceal corrupted MBs.

In [62], dispersed mode FMO was shown to be effective against a range of error burst lengths and in [63] loss rates as high as 10% could still be concealed with a hardly discernible impact on video quality. In [64], the dispersed mode FMO concept was extended across several frames to form a 3-D pattern of slices. This allowed concealment to take place in the temporal direction as well as within a frame.

To enhance error robustness in H.264/AVC, the encoder can send copies of some or all parts of a picture. Redundant slices [65] are coarsely quantized pictures that can avoid sudden drops in quality marked by freeze frame effects if a complete slice is lost. Methods to refine the selection of redundant slices [66] have also been designed. Thus in [66], MBs were selected for their relative impact on reconstruction and placed within FMO slices. The main weakness of the redundant slices solution is that these frames are discarded if not required. However, they can act as a way of protecting key frames in multicast [67] when it is difficult to retransmit. A subsidiary weakness of this scheme [67] is the delay in encoding and transmitting redundant frames, making it more suitable for one-way communication. If the redundant frame/slice replaces the loss of the original frame/slice there will still be some mismatch between encoder and decoder. However, the effect will be much less than if no substitution took place. A further possibility [68] is to use correctly-received reference pictures for reconstruction of redundant pictures rather than the reference pictures used by primary pictures. The decoder is able to select from a set of potential replacement redundant pictures according to the possibility of correct reconstruction.

In H.264/AVC, new types of frame [69], namely Switching Predictive/Intra frames (SP/SI-frame), were defined. This feature is introduced in the Extended Profile of the H.264/AVC standard. Though these frames were designed to support various applications such as smoothly switching between bitstreams at different coding rates for the purposes of congestion avoidance [70], they can also have a role in error resiliency and error recovery. The value of these frames was enhanced in [71], as it was shown that, by calculating the motion disparity in the transform domain, the space required to store switching frames in advance of their use was considerably reduced. In other words, because switching frames take up less storage space by the procedure in [71] their attractions increase.

In open-loop transmission, if an error occurs in a slice or MB within an inter-coded slice then the error will usually propagate in time until the next intra-coded picture (assuming periodic intra-refresh). If a feedback channel from the decoder to the encoder exists and a slice (or MB) has been corrupted it is possible during live streaming to send a request signal, allowing the encoder dynamically to replace the area affected by the error with intra-coded within the current picture. This may reduce the duration of the delay before inter-prediction is reset. However, due to the need for the encoder to transmit as soon as possible, coarse quantization of the intra-coded area can have undesirable side effects [72]. To avoid this problem [72], it is possible to request the encoder to predict the current picture from a picture that has been correctly received at the decoder. This allows temporal error propagation to be arrested without the need to dynamically send intra-coded slices or to wait until the next periodic intra-coded anchor picture (an I-picture or Instantaneous Decoder Refresh (IDR) picture in H.264/AVC).

Various acknowledgment or negative acknowledgment arrangements are possible, each with their advantages and disadvantages. It is also possible to limit or confine the spread of errors once the error has been notified [19] including through tracking of the errors at the encoder [73]. As has been mentioned in Section 1, H.264/AVC allows support of multiple reference frames in their various forms in a convenient manner. Some detractions of the use of multiple references are mentioned in Table 3. When latency constraints prevent a feedback channel, it is also possible to anticipate data or packet loss without the need for feedback,.

Another means of preventing temporal errors is to insert intra-refresh MBs amongst frames that are normally inter-coded, i.e. predictive P-frames. This procedure is an alternative to sending periodic intra-coded frames. Periodic intra-refresh frames have a number of detractions including: sudden increases in data rate for variable bit rate streaming; sub-optimal error concealment compared to motion-copy error concealment; and buffering delay due to the much large size of intra-coded frames. For semi-active video clips, ones without high motion coding complexity, it is unwise to employ periodic intra-refresh through I-pictures in a ‘lossy’ channel, as the relative drop in video quality at the receiver is then potentially larger, if one compares with cyclic line insertion at the same bit rate. Conversely, the insertion of a cyclic line of intra-refresh MBs usually results in an improvement in quality for semi-active sequences but also preserves an advantage for more active or fully active sequences. Though random insertion of intra-refresh MBs within a CBR stream is possible[3], this arrangement does not permit gradual decoder refresh (GDR). In GDR the stream is reset gradually to a clean state, from which future predictions can be made. However, forced intra-refresh with MB line can permit GDR. If there are N lines per picture then the worst-case GDR should take place within 2*N-1 pictures. The refresh rate can also be increased by cycling more than one line at a time.

The insertion of a cyclic intra-refresh line on a per picture basis is a relatively simple scheme. However, more complex adaptive intra-refresh schemes also exist. For example in [74] such a scheme required the encoder to keep track of which parts of the image area were recently refreshed. The encoder would then refresh those MBs which had more of an impact on error propagation. Alternatively the authors of [75] proposed a scheme in which FMO is combined with adaptive MB grouping. Because such schemes are at an individual MB level, they significantly increase the computational complexity arising from the required video content analysis. Moreover, methods using ‘explicit’ FMO also increase the bitrate and the degree of inter-packet dependency due to the need to include additional packets with the updated MB maps for every picture. Other adaptive schemes such as [76] have relied on feedback from the receiver. Once the decoder detects an error, it informs the encoder, which transmits intra-coded MBs to halt any error propagation. However, this procedure is unsuitable for conversational video services.

Still other schemes [12] [77] improve upon the deterministic application of the cyclic refresh line method by resolving a problem that exists at the boundary between a cleansed area and an area yet to be cleansed by intra-refresh. Suppose the direction of motion within the sequence is from a potentially corrupted region to a cleansed region. Then motion compensated prediction could predict a cleansed region from a suspect region. In that case, the cycle needs to revisit those predicted areas in order to undo the new corruption. It is possible to restrict the range of prediction [78] in these circumstances, but this

Table 3. Frame-level resilience.

Technique	*Usage*	*Remarks*
ASO	Allows slice reordering for out-of-order arrival of packets – improves end-to-end delay	Allows per MB decoding but decoder complexity can increase if ASO continues across picture boundaries
Data partitioning [25]	Allows reconstruction with DP-A only, low overhead, reduced packet size	Within frame protection only
FMO [39]	Aids error concealment, good reconstruction quality	Coding overheads make this unsuitable for low error rates; within-frame protection only
Redundant slices [66]	Protection against outright packet loss in poor channels, may be used in MDC	Large overhead, potential for encoder-decoder drift
SP/SI [69]	Switching between simulcast or multi-view streams, can support error resilience switching	Storage overhead of switching frames, limited bitrate improvement over periodic I-pictures
Multiple references [19]	Flexible reference frame selection counters packet loss	Usually requires feedback channel, large storage overhead at receiver decoder, limited improvement over single frame reference
Periodic I-frame [11]	Counters temporal error propagation, VCR functions and channel zapping supported	Significant data-rate increases and buffering delays, coding efficiency suffers
Intra-refresh MBs (cyclic line) [12]	Replaces costly I-frames in mobile communication, permits GDR	More overhead than random intra-refresh MBs
Intra-refresh MBs (random)	Replaces costly I-frames	GDR not guaranteed, not as efficient as adaptive MB refresh
Intra-refresh MBs (adaptive)	Replaces costly I-frames	GDR not guaranteed, may require feedback channel, computational intensive

ASO=Arbitrary Slice ordering, MB = Macroblock, DP-A = data partition type A, SP/SI = Switching P/I frames

[3] Within the JM implementation of the H.264/AVC reference software at http://iphome.hhi.de/suehring/tml/ [accessed 24/03/11]

will reduce coding efficiency. Alternatively, the direction of motion can be estimated [12] by observation of motion vectors in the border regions between the clean and yet to be cleansed regions. Based on this a refresh pattern is found. However, this method does not lend itself easily to hardware implementation and depends on estimates. However, the main gain from this technique seems to be an improvement in data rate of about 1% rather than improved video quality. On the other hand, an adaptive strategy switching between cyclic intra-refresh line during poor channel conditions and periodic refresh when conditions improve is a natural follow on from the results demonstrated in this paper.

It should be noted that intra-coding requires significantly less computation time than inter-coding, because of the absence of motion estimation, which can take up to 70% of computation. Thus, intra-refresh line insertion will reduce the computation time across the whole sequence, which is an attractive proposition for a video conferencing application.

4. SOME ERROR RESILIENCE PATENTS

In [79], a delayed version of the output bitstream is output on a block-by-block or string-by-string manner. Other header data and MVs are also duplicated. At the receiver original and delayed duplicate are compared in order to detect errors. Thus this system appears to be a low-level form or bitstream redundancy.

The type of error resilience is varied in [80] according to the type of frame, whether it is a predictive coded P-frame or a bi-directionally predictive B-frame. The intention is to offer less protection to B-frames as they are not reference frames for other frames. However, notice that, in H.264/AVC, B-pictures can be used as references for coding other B-pictures. Moreover, both references for a B-picture can come from previous or future pictures. In [81], different picture prediction patterns are examined for their error resiliency functionality.

In [82], when a periodic, requested, or scene cut intra-coded frame would normally occur, another later frame is chosen. This later frame should lie mid-way in time between two intra-coded frames. The later frame is then intra-coded. Subsequently, frames before the inserted intra-frame are predicted in reverse from that frame and those after it are forward predicted. The consequence is that for these frames (the ones before and after the inserted intra-coded frame), the prediction path is shortened.

A problem that often occurs when bit-rate transcoding (changing from one bitrate at one compression ratio to a lower compression ratio to accommodate available bandwidth) takes place is how to re-arrange the error resilience provision. The apparatus in [83] is about making that rearrangement through the replacement of resynchronization markers and intra-coded MBs within the stream.

Side information can be sent by an encoder in a bitstream which can aid error concealment of already received frames found to be in error at the decoder. A decoder can request such information and [85] is concerned with embedding such information in the bitstream. In fact, SEI messages might possibly serve a similar purpose in H.264/AVC. The patent [85] is about the construction of such side information that could be sent through a side channel, allowing the identification of data that could be dropped by the decoder. Another patent that considers embedding content information is [86]. As a variant on the theme of transmitting side information [87] considers transmitting reliable video frames on a reliable side channel as a way of reconstructing frames that may have been received in error. In a sense, there are similarities to the concept of distributed video coding.

5. ERROR CONCEALMENT

Despite all the error-resilient techniques that might be applied to protect the bitstream, sometimes, the extent of errors overcomes the error correction capacity. In this situation, the affected slices are lost and the corresponding MBs are not decoded. In order to minimize the visual impact resulting from the undecoded MBs, error concealment (EC) techniques are commonly applied at the decoder. Error concealment is basically the action of hiding the effects of errors. Because error concealment is not a standardized tool in the H.264/AVC codec standard, this has left plenty of room for improvements by researchers. In industry, this opportunity has also allowed companies to distinguish their products from other competing products. As a result, this situation often leads to the filing of patents to protect a company's intellectual property and products from copying.

Error concealment schemes can be defined as a set of procedures performed at the decoder on the lost slices, aimed at increasing the viewer's perceived video quality. Prior to concealment, the decoder has to detect the existence of errors. This can be achieved by checking the packet sequence number in order to find discontinuities, which imply that packets were lost. Afterwards, even if all packets were received, some might contain errors. To identify those erroneous packets, the existing channel codes can be analysed. Even if these fail, errors can still be detected by the entropy decoder (if illegal codewords are found) or by the decoder itself (if syntax violation is verified). If packets are found in any of these detection phases, error concealment can then be enabled to minimize the visual impact.

5.1 Error Concealment Types

Numerous error concealment techniques have been developed using different strategies and different types of data. Herein, error concealment techniques are categorised into three groups depending on the video redundancy used to aid the concealment: spatial, temporal and spatio-temporal.

Spatial error concealment

Techniques which exploit exclusively data from the current time instant are known as spatial error concealment [88] [89] [90]. This means that lost MBs are reconstructed using data interpolation from the available neighbouring MBs. The concealment performance of spatial EC techniques is highly dependent on the area being reconstructed and works best for small, homogeneous and areas with limited details. Thus, it is mainly used for intra-predicted frames, in which slices usually represent smaller frame areas than in inter frames. Additionally, no temporal error propagation is introduced from previous frames.

As examples of patent applications, in [91] and [92], the inventors described a spatial error concealment method for intra predicted pictures that reconstructs the missing MBs based on the intra prediction direction of neighboring blocks.

Temporal error concealment

In most cases, videos have a high temporal correlation between frames, and this is where most of the video compression comes from. As a result, it is obvious that previous frames can be efficiently [89] [93] exploited to reconstruct any missing areas from the current frame. A basic implementation is the simple copy of the lost pixels in the collocated positions from one of the previous frames (Frame Copy). This works well when there is medium to low motion activity. For sequences with higher motion activity, better techniques can be implemented which exploit the typical motion characteristics by predicting the motion vectors of the current slice being concealed using motion information from the previous frame (Motion Copy). These techniques work best for videos with high temporal redundancy.

As examples of temporal error concealment, in [94] [95], the inventors describe methods in which a statistical measure is applied to a set of candidate motion vectors from multiple frames to assist the generation of a candidate motion vector to conceal a missing slice in the current frame.

Spatio-temporal error concealment

As in most things, the more information is used the better will be the result. In error concealment, the same concept applies and consequently hybrid spatio-temporal error concealment [96][97][98][99] can be applied. Techniques which use information from the current frame as well as from previous decoded frames can typically perform better. In some cases, some parts of the frame might be reconstructed with spatial concealment, others by temporal concealment or even by a combination of both spatial and temporal. In either case, concealment criteria are essential to find which one reconstructs the lost slice the closest to the original.

As patent examples, in [100] [101] the inventors describe a method to concealing a missing block by using a spatial vector to construct a spatial reference block, and using this spatial reference block to generate a spatial prediction of the lost block.

Optimization Criteria

Despite the block-based coding approach of video coding, it is highly likely that there will be small pixel differences at MB edges. Additionally, the H.264/AVC standard includes an in-loop deblocking filter that further smoothes the MB edges. Therefore, MB edge smoothness has been extensively employed as a minimization criterion to choose the best concealment, when multiple options are available in [102]. Later on, work in [103] extended this technique to include temporal smoothness as a criterion.

Table 4 is a summary of the advantages and disadvantages of each error concealment type. One can see that the simpler the technique the lower the reconstruction quality and vice-versa.

Table 4. Comparison between different error concealment types.

	Advantages	*Disadvantages*
Temporal Prediction	Simple; efficient if MVs are available	Lower efficiency if MVs are estimated
Spatial Prediction	Simple; efficient for small areas	Blurring effect in non-homogeneous areas
Spatio-temporal Prediction	Best results	Computational complexity

5.2 Other concealment challenges

Reconstructing a lost slice is a challenging task due to the uncertainty about the original data. Even so, it is also possible that the whole frame might be lost, making it impossible to exploit spatial EC techniques. This scenario is particularly real in applications with a low bandwidth and using small frame sizes. In this case, one frame is packetized into a single slice to avoid further network overheads, meaning that a lost packet results into a whole frame loss. A lost packet hence results in an entirely missing frame [104]. In [105], the inventors describe a bi-directional temporal error concealment method for whole frame losses where bi-directional estimations for each pixels of the lost frame are calculated.

6. CURRENT & FUTURE DEVELOPMENTS

Much has been accomplished in the field of error resiliency and concealment for digital video. This paper has surveyed a good number of the most interesting and important algorithms proposed in the last decades. Firstly, the paper reviewed video error resiliency schemes for enhanced robustness to transmission errors. Secondly, the paper reviewed error concealment algorithms. Despite all the forms of protection available, errors will still be present when the correction capacity is reached. In this case, it is up to the error concealment techniques to dissimulate as much as possible the visual effect resulting from undecodable slices. It can be predicted that, in the near future, novel and more complex schemes will be developed to cope with the ever increasing bitstream error sensitivity resulting from the continuously growing compression ratios of modern video codecs. This is supported by the growth in computational power of portable devices.

CONFLICT OF INTEREST

We declare that we have no financial and personal relationships with other people or organisations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled, “Recent Innovations in Video Error Resilience and Concealment”.

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