DIGITAL WATERMARKING OF MPEG-2 CODED VIDEO IN THE BITSTREAM DOMAIN

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ABSTRACT

Embedding information into multimedia data, also called watermarking, is a topic that has gained increased attention recently. For video broadcast applications, watermarking schemes operating on compressed video are desirable. We present a scheme for robust watermarking of MPEG-2 encoded video. The watermark is embedded into the MPEG-2 bitstream without increasing the bit-rate, and can be retrieved even from the decoded video and without knowledge of the original, unwatermarked video. The scheme is robust and of much lower complexity than a complete decoding process followed by watermarking in the pixel domain and re-encoding. Although an existing MPEG-2 bitstream is partly altered, the scheme avoids visible artifacts by adding a drift compensation signal. The scheme has been implemented and the results confirm that a robust watermark can be embedded into MPEG encoded video which can be used to securely transmit arbitrary binary information at a data rate of several bytes/second. The scheme is also applicable to other hybrid coding schemes like MPEG-1, H.261, and H.263.

1 INTRODUCTION

In todays video delivery and broadcast networks, issues of copyright protection have become more urgent than in analog times, since the duplication of digital video does not result in the inherent decrease in quality suffered by analog video. One method of copyright protection is the addition of a "watermark" to the video signal. The watermark is a digital code embedded in the video which typically indicates the copyright owner or, if applied to individual copies of the video, the identity of the receiver of each copy. This allows illegally reproduced copies to be traced back to the receiver from which they originated, as shown in Fig. 1. For watermarking of video, a number of different characteristics of the watermark are desirable. These requirements include invisibility (the embedded watermark should be invisible), security (without knowledge of the exact parameters, unauthorized removal of the watermark must be impossible once it has been embedded, even if the basic scheme of watermark embedding is known), robustness (the watermark should be such that it cannot be manipulated without, at the same time, degrading the perceived quality of the video significantly), low complexity, compressed domain processing (for video stored in compressed format, decoding+watermarking+re-encoding is not feasible), constant bit-rate (the watermarked sequence must not occupy more bit-rate than the unwatermarked), and interoperability between uncompressed and compressed domains (the watermark is embedded into compressed video and must be retrievable from decompressed copies).

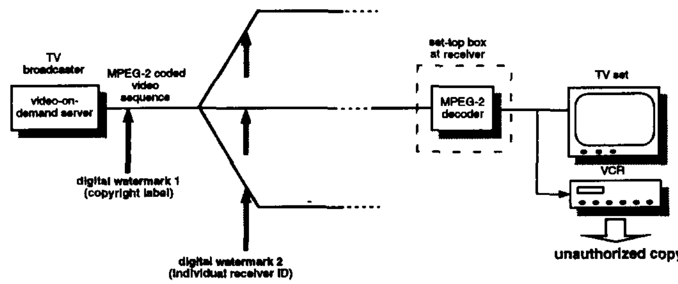

Figure 1. Broadcasting of video with individual watermark embedding at the transmitter side.

Previous work on watermarking includes watermarking of still images [1, 2, 3, 4, 5], audio [6], and multimedia data in general [7]. We present a new scheme for watermarking of MPEG-2 compressed video which is of considerably lower complexity than schemes for watermarking of uncompressed video which require decompression and re-compression when a compressed video sequence has to be watermarked. For pay-per-view broadcast applications with individual encryption, watermarking of compressed video gives the possibility of performing the watermarking at the receiver as shown in Fig. 2. This reduces the complexity on the server side and makes individual watermarking of different copies of a video more feasible. If decryption and watermarking are implemented in a single chip or ASIC, and the decrypted signal is not accessible before watermarking, this is a secure mechanism.

In section 2, we briefly introduce a scheme for watermarking of uncoded video that is based on ideas from spread spectrum communications. In section 3, we extend the scheme to the domain of MPEG-2 compressed video. We incorporate the watermark into pre-compressed MPEG-2 bitstreams, and can retrieve it from the video even after decoding and without knowledge of the original video. Since the encoded video is partly altered, we have to consider drift due to motion compensation which we can compensate within our scheme, as explained in section 3.2. In section 4, we discuss practical aspects. We have implemented our scheme for watermarking of MPEG-2 encoded video which works

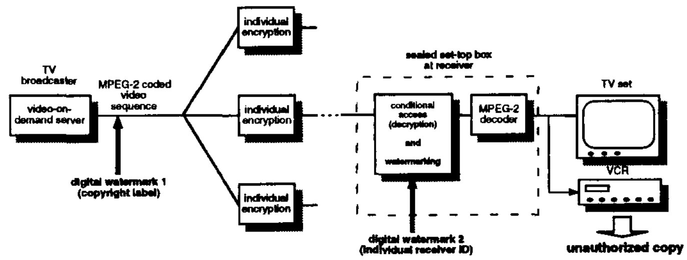

Figure 2. Broadcasting of video with individual watermark embedding at the receiver side.

robustly and can embed arbitrary watermark information into encoded video at a data-rate of several bytes/second.

2 DIGITAL WATERMARKING OF UNCODED VIDEO IN THE PIXEL DOMAIN

The basic idea of watermarking for video is the same as for images [2, 5, 7]: adding a noise-like signal to the video pixels that is below the threshold of perception and that can not be identified, and thus removed, without knowledge of the parameters of the watermarking algorithm. Our approach to accomplish this is a direct extension of ideas from direct-sequence spread spectrum communications [8]. The approach in [7] is similar and was developed independently.

Fig. 3 shows the basic steps of watermark embedding in the pixel domain. For a mathematical formulation, please refer to [9]. To embed a watermark, the information bits $a_j \in \{-1, 1\}$ to be hidden are first spread by a large spreading factor cr, in analogy to spread spectrum communications called the chip-rate. The purpose of spreading is to embed one bit of information into many (exactly, into cr) pixels of the video sequence. The spread bits are then modulated with a pseudo-noise sequence, yielding the watermark signal. The amplitude of the watermark signal may be amplified before finally adding it to the pixels of the line-scanned video sequence. The amplification factor can be varied according to local properties of the image and can be used to exploit spatial and temporal masking effects of the human visual system (HVS). Because we use a

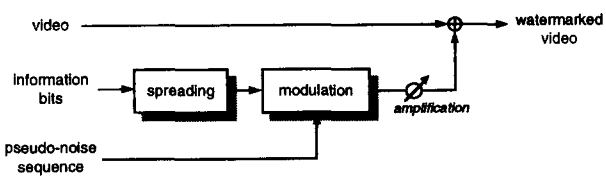

Figure 3. Scheme for embedding information bits into video pixels.

pseudo-noise signal for modulation, also the watermark is a noise-like signal and thus difficult to detect, locate, and manipulate.

The recovery of the hidden information at the watermark decoder is easily accomplished by correlating the watermarked video signal with the same pseudo-noise sequence that was used in the coder (see Fig. 4), where correlation can be understood as demodulation followed by summation over the correlation window. In our case, the width of the correlation window for each information bit is just the chip-rate. If the peak of the correlation is positive, the current transmitted information bit is +1. If the peak of the correlation is negative, the current transmitted information bit is −1. After decoding of one bit, we proceed to the next cr pixels containing the next bit. A condition for the scheme to work

Figure 4. Scheme for retrieving information bits from watermarked video pixels.

is that at the receiver the same unshifted pseudo-noise sequence is used that was used at the transmitter. Thus, even if the receiver knows the basic scheme, he cannot recover the information without knowledge of the used pseudo-noise sequence and its possible shift. Please note also that we do not use the original video sequence for retrieving the watermark. However, if we do know the original sequence, we can make the scheme more robust by subtracting it from the watermarked sequence prior to correlation.

3 DIGITAL WATERMARKING OF CODED VIDEO IN THE MPEG-2 BITSTREAM DOMAIN

MPEG-2 bitstream syntax allows for user data being incorporated into the bitstream. However, this is not a suitable means of embedding a watermark, since the user data can easily be stripped off the bitstream, and vanishes after decoding anyway. Again the key idea is to incorporate the watermark into the signal itself, i.e., into the bitstream representing the video frames.

In the following, we present a scheme for watermarking of previously encoded video that is compatible with the scheme for watermarking of uncoded video given in the previous section. Again, for a more rigid but less comprehensive formulation of the algorithm, please refer to [9].

3.1 Basic scheme

The principle of MPEG-2 video compression is motion-compensated hybrid coding. I-frames are split into blocks of 8 by 8 pixels which are compressed using the DCT, quantization, zig-zag-scan, run-level-coding and entropy coding (see Fig. 5). P- and B-frames are motion compensated and the residual prediction error signal frames are split into blocks of 8 by 8 pixels which are compressed in the same way as blocks from I-frames. Instead of adding the watermark in

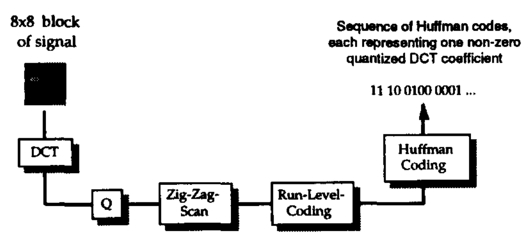

Figure 5. Encoding of one 8x8 pixel block.

the pixel domain, we extract, for each encoded 8×8-block of the video, the corresponding block from the watermark signal. We then transform the watermark block using the

DCT, and add the two blocks in the transform domain. Figure 6 shows the corresponding generic block diagram. On

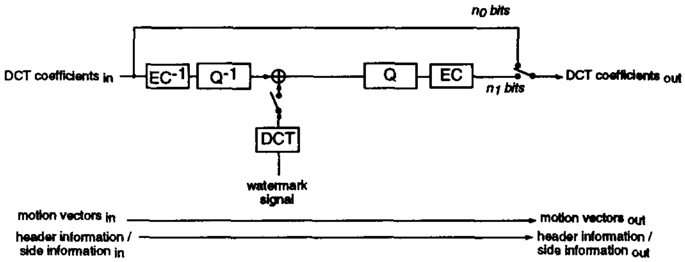

Figure 6. Generic scheme for watermarking of compressed video

the left side, the incoming MPEG-2 bitstream is split into header and side information, motion vectors (for motion compensation) and DCT encoded signal blocks. Only the latter part of the bitstream is altered; motion vectors and header/side information remain untouched and are copied to the watermarked MPEG-2 bitstream. The DCT encoded signal blocks are represented by a sequence of Huffman codes, each representing one (run,level)-pair and, thus, one non-zero DCT coefficient of the current signal block. Each incoming Huffman code is decoded (EC^{-1}) and inversely quantized (Q^{-1}) (where "inverse quantization" means mapping from the quantizer index to the quantizer representative). After inverse quantization, we have one quantized DCT coefficient of the current signal block. We then add the corresponding DCT coefficient from the transformed watermark block, yielding a watermarked DCT coefficient. We then quantize (Q) and Huffman encode (EC) the watermarked coefficient, together with its preceding run of zero coefficients. We compare the number n_1 of bits for the new Huffman codeword with the number of bits n_0 for the old, unwatermarked coefficient. The (run,level)-codewords in MPEG-2 are fixed. Fig. 7 shows the number of bits for the (run,level)-codewords specified in the MPEG-2 VLC tables [10]. (run,level)-combinations that are not specifically represented in the VLC tables are coded with an escape code of 24 bits. As can be seen, the number of bits can be the same even for different (run,level)-pairs to be encoded. Since we do not want to increase the bit-rate of the video

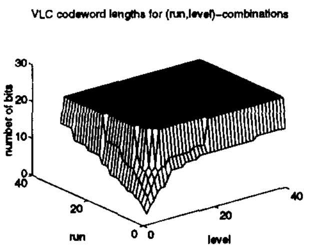

Figure 7. MPEG-2 VLC codeword lengths for (run,level)-codewords.

bitstream, we only transmit the watermarked coefficient if $n_1 \leq n_0$. Otherwise, we transmit the unwatermarked DCT coefficient and can not embed the watermark into this DCT coefficient. Since we embed one bit of watermark information into many pixels and thus many DCT coefficients, it does not matter if we have to omit some of them as long as there are enough DCT coefficients left that are watermarked. If necessary, we can increase the chip-rate, increasing the robustness to the desired level, but at the same time decreasing the data rate for the watermark. We should note that only existing (non-zero) DCT coefficients of the input bitstream are used for watermarking. Among the non-zero coefficients, only those are really watermarked that do not increase the bit-rate. Typically, around 15 – 30% of the DCT coefficients are altered, of course depending on scene structure and bit-rate. An interesting implication of the fact that only existing (non-zero) DCT coefficients of the input bitstream are watermarked is that the embedded watermark depends on the image signal. In areas where only low spatial frequencies are in the image, also the watermark can contain only low-frequency components. This complies with human vision: more watermark signal energy is embedded where it is less visible.

One problem of compressed-domain processing of MPEG-2 video bitstreams is drift. Motion-compensated hybrid coding is a recursive scheme where motion compensated predictions from previous frames are used to reconstruct the actual frame, which itself may serve as a reference for future predictions, and so on. Once a degradation occurs in the video sequence, it may propagate in time, and even spread in space [11]. Adding a watermark is such a degradation. Furthermore, since all video frames are watermarked, watermarks from previous frames (by motion compensation) and from the current frame may accumulate in the current frame and result in visual distortion, if no countermeasures are taken. Therefore, we have to add a drift reduction signal besides the watermark signal that compensates for watermark signals from previous frames.

3.2 Scheme with drift compensation

If we want to compensate the drift by adding a drift compensation signal, we have to add exactly the difference of the predictions made at coder and decoder. This idea is similarly known in the context of trans-coding of existing MPEG bitstreams [12]. Figure 8 shows an according ex-

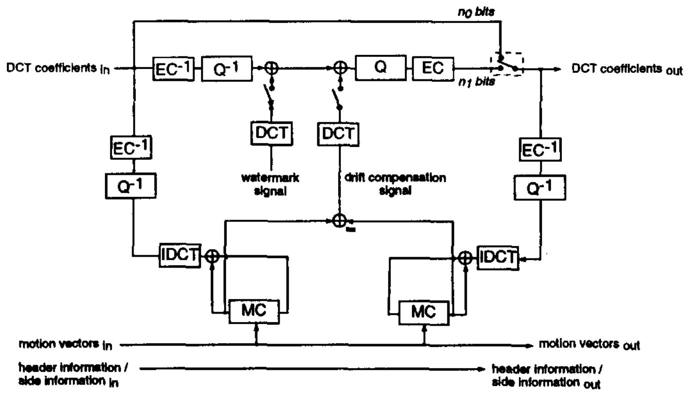

Figure 8. Scheme for watermarking of compressed video with drift compensation.

tension of our watermarking scheme with calculation of the drift compensation signal as the difference of the (motion compensated) predictions from the unwatermarked bitstream (left MC prediction block) and the watermarked bitstream (right MC prediction block). If no watermark is embedded, watermarked and unwatermarked bitstreams are the same, the predictions made from them are the same, and the drift compensation signal is zero. The depicted scheme works, but can be further simplified. Motion-compensated prediction can be regarded as a linear operation, if no clipping is applied. Thus, the two MC prediction blocks of Fig. 8 can be consolidated into one. Additionally, entropy coding and decoding can be moved out of the loop, yielding the simplified scheme of Fig. 9.

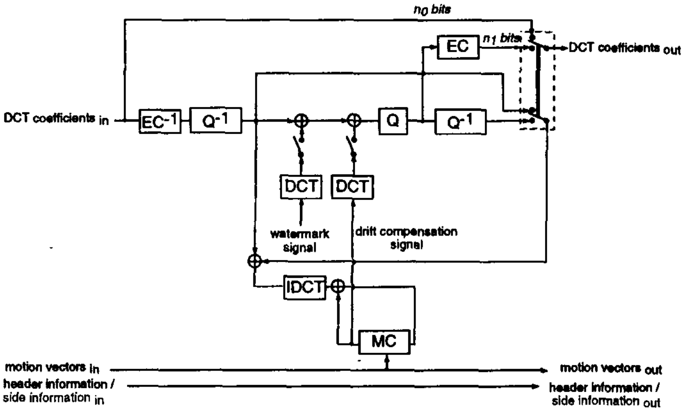

Figure 9. Simplified scheme for watermarking of compressed video with drift compensation.

4 IMPLEMENTATION AND SIMULATION RESULTS

We have implemented the scheme of Fig. 8 as a C program which takes an MPEG-2 bitstream as its input, parses the bitstream and writes it to a new file. Only those parts of the bitstream containing VLC codewords representing DC- and AC-coefficients of DCT blocks are located and replaced by VLC codewords representing DC- and AC-coefficients of the same block *plus watermark*. The complexity is much lower than the complexity of decoding plus watermarking in the pixel domain plus re-encoding. An implementation of the scheme of Fig. 9 is under development and is expected to be of lower complexity than decoding alone. Typical parameters are $\alpha = 1 \ldots 5$ for the amplitude of the watermark and $cr = 10{,}000 \ldots 1{,}000{,}000$ for the chip-rate, yielding data rates for the watermark of 1.25...125 bytes/second for NTSC TV resolution. The embedded watermark can be retrieved from the watermarked video without knowledge of the original video and is robust against linear and nonlinear operations like further transform coding, filtering, quantization in pixel or frequency domain, and others. Unfortunately there is no robustness measure available which allows a correct comparison of robustness to other watermarking schemes [2, 5, 7]. Figure 10 gives a visual impression of some example attacks on the watermarked video that the watermark survived.

5 CONCLUSIONS

We have presented a new scheme for watermarking of MPEG-2 compressed video in the bitstream domain. Working on encoded rather than on unencoded video is important for practical watermarking applications. The basic idea is embedding the watermark in the transform domain as represented in the entropy coded DCT coefficients. The watermark can be retrieved even from the decoded sequence

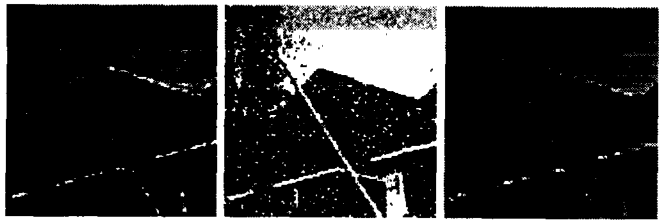

Figure 10. Details of a video sequence attacked by different approaches. The watermark survived all those attacks. Left: blockwise DCT compression; middle: addition of gaussian and impulse noise and an offset, right: local permutation of pixels.

and without knowledge of the original, or from an analog copy recorded on a video tape. With appropriate parameters, the watermarking scheme in the MPEG-2 bitstream domain can achieve data rates for the watermark of several bytes/second while being very robust against friendly or hostile manipulations. The principle can also be applied to other hybrid coding schemes, such as MPEG-1, ITU-T H.261, or ITU-T H.263.

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