Chapter 8

> "Reading maketh a full man; conference a ready man; and writing an exact man."
>
> Francis Bacon (1561-1626)

Conclusions & Further Work

Today virtually all multimedia production and distribution is digital. Therefore one can enjoy all the advantages of digital technology. The downside is that it becomes very easy to pirate copyrighted material as digital technology permits easy and unlimited copying without any loss in quality whatsoever. In order to combat this threat, one can use digital watermarking. The research carried out during this PhD and described in this thesis, addresses this difficult issue from the perspective of broadcast monitoring. This is just one of many possible applications of watermarking technology, as already shown in Chapter 1.

This chapter will conclude the work presented in this thesis and suggest further research directions. The complete list of author's publications can be also found here.

8.1 Conclusions

This thesis gradually described the building of a blind video watermarking system suitable for broadcast monitoring applications. Starting with a simple spatial domain technique, the system was gradually refined in order to meet the requirements imposed by broadcast monitoring. In the end, after passing several successive steps in order to improve the performance of the system, the result was a DWT-based, high capacity blind video watermarking system robust to a wide range of geometrical and non-geometrical attacks which meets and in some cases even exceeds (sometimes by far) the broadcast monitoring requirements outlined by EBU [Cheveau et al, 2000]. This good performance was achieved by using a combination of communication techniques (spread spectrum, matched filtering, error correction coding), human perception (HVS models) and image processing techniques (image registration and pattern recognition).

Although EBU's recommendations specify a watermark capacity of 64 bps, the target of this research was to improve this figure as much as possible. This aim was achieved by regarding the watermarking channel as a communication channel which therefore can be protected by using FEC. Given the difficult nature of this channel, one needs powerful error correction in order to boost the performance of the system. This requirement is met by the Turbo codes, described in Chapter 4. Using this state-of-the-art FEC, the performance of the system increases significantly, as the comparative results provided in Chapter 5 and Chapter 6 show. Robustness to various attacks is a very important requirement in a watermarking system. In order to cope with this requirement, one would like to embed more energy into the host video. Unfortunately this is quite difficult since the invisibility of the mark has to be preserved. One solution for overcoming this aspect is to use HVS models which will accurately specify the maximum amount of modification for each pixel/coefficient while the invisibility constraint is still achieved. Therefore an investigation of the existing HVS models (mostly developed in the context of image compression) was carried out and the selected models were simplified, improved and adapted to the specific case of digital watermarking. Their efficiency and their benefits were presented in Chapter 3, Chapter 5 and Chapter 6.

One has the possibility of inserting a watermark either in spatial domain or in the transform domain. It is largely agreed that spatial domain is not as good as transform domain in terms of capacity/robustness, but has the advantage of simplicity. When the capacity is not a major issue, as in the case described in Chapter 7, this advantage is very important.

Speaking by transform domain watermarking, it is very important to choose a proper transform. Chapter 5 showed that the DCT is an important candidate in this respect. DCT domain watermarking offers much better performance compared with the spatial domain watermarking techniques described in Chapter 3. An important aspect of this research was to investigate the use of wavelet transform in digital watermarking. This investigation led to one of the main contributions of this thesis: developing a high capacity, robust, wavelet-based blind video watermarking system which takes advantage of the properties of the wavelet transform. The importance of using these advantages is well illustrated by the results presented in Chapter 6. The performance of the system is further improved by using HVS model and advanced FEC. Chapter 5 and Chapter 6 largely confirmed the superiority of the DWT against the DCT.

It has been clearly shown that DWT offers a much higher capacity/robustness report than DCT, even when using a much simpler HVS model.

Unfortunately the watermarking systems presented in Chapter 5 and Chapter 6 have one common negative characteristic: they cannot cope with geometrical attacks, unless an extensive search is performed in order re-synchronise the system. Using a 3-D sliding window correlator as suggested in Chapter 5 can solve this problem, but this approach has the major drawback of being very computationally expensive (difficult to use in a real time system), so it is preferably to employ other methods less demanding. Finding such methods and using them for blind video watermarking was another main challenge of this research, and represents the most important contribution of this thesis.

This problem was addressed in Chapter 7. This chapter shows that, by using image registration techniques (adapted to the specific of digital watermarking) in conjunction with a reference watermark, this problem can be solved much easier. The use of LPT/LLT in image registration was known from long time, but giving the blind nature of video watermarking, this technique could not be used in this case, since it requires the presence of the original image/video. The technique proposed in Chapter 7 shows that this problem can be solved by using a reference watermark in order to compensate for the unavailability of the original, and therefore achieving “blind registration”. The reference watermark is embedded in spatial domain in order to keep the system as simple as possible. Using a separate reference watermark is advantageous because one can keep the high capacity of the system unchanged. Moreover the main watermark is embedded in wavelet domain, as suggested in Chapter 6, and therefore one can benefit from the advantages offered by the DWT transform. The net result is a DWT-based, high capacity blind video watermarking system robust to a wide range of geometrical and non-geometrical attacks. The performance of the final system is summarised in a tabular form, and compared with the EBU recommendations. This comparison, presented in **Table 8-1**, fully illustrates the performance and the capabilities of the proposed system.

Although the EBU recommendations do not specify (at this stage) any combined attacks, the system presented Chapter 7, can handle a varied range of combined attacks: shift combined with MPEG2 compression (>3Mbps MPEG2), shift combined with cropping (providing that approximately 30% from the original frame is still available), shift combined with cropping and compression, and even scaling combined with rotation (up to 120% scaling combined with up to 20^0 of rotation). Additionally, even if is not typical to video, the system can cope with very low quality JPEG compression.

Parameter	**EBU Recommendations**	**Proposed System**
GENERAL PARAMETERS OF THE SYSTEM		
Watermarking Minimum Segment (WMS)	1- 5sec	min 1sec
Data capacity	64bits/WMS	≥1200bits/WMS @ 2Mbps MPEG2
Probability for error-free payload per WMS	$>10^{-8}$	10^{-8}
False positive probability per WMS	$<10^{-8}$	$<10^{-8}$
Format of original and watermarked signals	ITU-R 601 (ITU-T BT.656)	ITU-R 601 (ITU-T BT.656)
Watermark recovery	Blind	Blind
ROBUSTNESS TO ATTACKS		
MPEG2 compression	2-6Mbps MPEG2	2-6Mbps MPEG2
VHS attack	YES	YES (easy)
Colour-space conversion	YES	Invariant
Collusion	YES	YES (easy)
Multiple Watermarks	YES	YES
Shift	up to 320x288	higher than 320x288
Scaling	desired: 200%, -50% best achieved: 140%, -70%	180%, -50%
Aspect-ratio conversion	16:9 ↔ 4:3	16:9 ↔ 4:3 (easy) 200%, -100%
Small rotation	up to 2^0	up to 2^0
Noticeable rotation	up to 10^0	up to 70^0
Small bend/shear	up to 2^0 (10^0)	NO
Cropping	minimum size 320x288	Even smaller than 200x200
Frame rate changing	24Hz ↔ 25Hz ↔ 30Hz	Invariant
Slow motion	3:1	Invariant
Combined attacks	NOT SPECIFIED	YES (wide range)

Table 8-1 The performance of the system compared with EBU's recommendations.

Starting from mid nineties quite a lot of companies are offering watermarking techniques for different market sectors. The international standardizing bodies and professional groups started several attempts to create some standards and recommendations for this potentially huge market. Although currently a watermarking standard is still missing, at least standardising bodies like EBU have issued some recommendations, making the first step in the direction of a standard. The direct result of the dissension within the watermarking world (from the industry's perspective), was that currently most of the digital technologies are not using watermarking techniques, opting instead in favour of cryptographic protection techniques like CSS (Content Scrambling System) for DVD and CI (Common Interface) for DVB. I spite of this, the watermarking research is a dynamic "market" with the research still going on in order to obtain better systems, proving once more that the interest in watermarking technology is still high. It is expected that sooner or later watermarking techniques will be probably incorporated in any (digital) multimedia system, especially since the CSS system was cracked pretty soon after the public release of the DVD and the DVB is confronted with a lot of piracy. Therefore the digital watermarking seems to have a very bright future ahead.

8.2 Further Work

In respect to EBU's recommendations, the system proposed in Chapter 7 has only one flaw: it cannot cope (directly) with geometric attacks like bending/shearing, unless an extensive search is performed. This is not a major issue, since the search space is quite limited (EBU recommends robustness to unnoticeable/small bending/shearing only). Obviously one would like to address this problem more efficiently in the future. On a related note, one could extend the system to cope with any affine transformation; in which case the bending/shearing would not be an issue anymore.

Choosing the best wavelet basis is very important. It would be very interesting to compare the performance of the system for different wavelet families. This could be difficult because of the lack of HVS models for most wavelet basis. Complex wavelets and their properties could offer a handy way of overcoming the affine transformations and maybe even non-affine transformations (StirMark like attacks). Using these wavelets could even improve the capacity of the system, although at this moment there is no HVS model available for this wavelet.

As this thesis has shown, the HVS models play a central role in any watermarking system. The importance of a reasonable HVS model is paramount. The proposed system uses a very simple HVS model, and yet can achieve very good results. It is likely that using a more advanced HVS model will further improve the performance of the system and will reduce even more the watermark visibility. Using a JND-like model could result in optimum watermark embedding.

A more in depth analysis of the multiple watermarking case could be also performed, in order to asses exactly how many different watermarks can be inserted in the video sequence. This problem is obviously very closely related with the HVS model. It is likely that this will be the major limiting factor in having several watermarks on top of each other, since as the experiments show and literature agrees [Cheveau et al, 2000] different keys usually lead to near orthogonal watermarks and is not a major problem to have several watermarks on top of each other (from this point of view). This would evidently involve extensive (subjective) visibility tests in order to determine the impact of multiple watermarks on the visibility.

Although at the moment this is not a major concern (at least not from the broadcast monitoring perspective), the ownership deadlock problem could be sooner or later addressed. One way to solve this very difficult problem is to use One Way Hashing Functions and time stamps. The presence of a third party may be necessary in order to authenticate the keys. Generally the ownership deadlock is still an open problem and does not raise a significant interest in the watermarking community at this time.

Finally, although this is not specified at this time in the EBU recommendations, it would be very interesting to analyse the performance of the system under various other compression standards: MPEG4/DivX, MPEG7, MPEG21, JPEG2000.

8.3 List of Author's Publications

"Adding Robustness to Geometrical Attacks to a Wavelet Based, Blind Video Watermarking System", C. Serdean, M. Ambroze, M. Tomlinson, G. Wade, Proceedings of the IEEE International Conference on Multimedia and Expo – ICME 2002, Lausanne, Switzerland, 26-29 August 2002.

"DWT Based Video Watermarking for Copyright Protection, Invariant to Geometrical Attacks", C. Serdean, M. Ambroze, M. Tomlinson, G. Wade, Proceedings of the 3'rd International Symposium on Communication Systems, Networks & Digital Signal Processing – CSNDSP' 2002, Staffordshire, UK, 15-17 July 2002, pp. 312-315.

"Combating Geometrical Attacks in a DWT based Blind Video Watermarking System", C. Serdean, M. Ambroze, M. Tomlinson and G. Wade. Proceedings of the 4'th EURASIP-IEEE International Symposium on Video/Image Processing & Multimedia Communications – VIPromCom 2002, Zadar, Croatia, 16-19 June 2002, pp. 263-266.

"Protecting Intellectual Rights: Digital WM in the Wavelet Domain", C. Serdean, M. Tomlinson, G. Wade & M. Ambroze, Proceedings of the IEEE International Workshop "Trends & Recent Achievements in Information Technology", Cluj-Napoca, Romania, 16-18 May 2002, pp.70-77.

"DWT Based High Capacity Blind Video Watermarking, Invariant to Geometrical Attacks", C. Serdean, A. Ambroze, M. Tomlinson and G. Wade, Accepted for publication in IEE Proceedings Vision, Image and Signal Processing, Submitted December 2001 (in press).

"Turbo Code Protection of a Video Watermarking Channel", A. Ambroze, G. Wade, C. Serdean, M. Tomlinson, J. Stander and M. Borda. Published in IEE Vision, Image and Signal Processing, Vol.148, No.1, February 2001, pp. 54-58.

"Watermarking Uncompressed Video: an Overview", G. Wade, C. Serdean, A. Ambroze, M. Borda & I. Nafornita. Proceedings of the IEEE Symposium on Electronics and Telecommunications, 'Etc. 2000', 23-24 November 2000, Timisoara, Romania, Vol.1, pp. 2-15. (Invited Paper)

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Parts of the work described during Chapter 5 were carried out in collaboration with Dr. Adrian Ambroze. The main contribution of the author was related with watermark embedding (HVS, modulation techniques, system improvements) and watermark recovery (2-D sliding correlator, visibility tests). Dr. Ambroze was in charge with channel protection (pdf of the channel, Turbo coding, performance assessment) and attack characterisation. Also most of the work related with watermark recovery (3-D sliding correlator, several performance tests) was carried out in parallel with Dr. Ambroze.

The author also wants to thank Dr. Ambroze for his assistance during the many visibility/robustness tests carried out and for supplying him with several performance diagrams (**Figure 5-13** – **Figure 5-19**) which saved allot of computation time. The author gratefully acknowledges the above contributions and wishes to thank Dr. Ambroze for a fruitful collaboration.