Advanced Watermarking and its Applications

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Abstract

Audio watermarking is a technique for the transmission of additional data along with audio material within existing distribution channels. Recent research has produced a number of algorithms for the embedding and retrieval of watermarks in audio signals. While most known systems operate in the linear domain, few are capable of embedding watermarks into compressed material.
This paper investigates the different areas of applications and their specific requirements with respect to watermarking technology. Both watermarking in linear and compressed domain are contrasted in their concepts and properties and recent technological advances are described.

1 Introduction

Watermarking is the imperceptible transmission of additional data along with some cover data (often multimedia data) by so-called watermarks [1]. It offers means to "attach" data to audiovisual material in a way that the original media format is not altered by the embedding process. In this sense, watermarking is a method for establishing a hidden data channel within existing channels for audiovisual communication which does not require additional infrastructure. A very basic view of watermarking as a compatible data channel is shown in Fig. 1. The watermarking embedder takes cover data along with the data to be embedded to form the watermarked content, e.g. the watermarked music. After distribution/storage in conventional form, the watermarked content may be presented for consumption by usual means of rendering. At the same time, a watermark extraction stage will be able to retrieve the embedded data from the watermarked content.

While watermarking techniques have recently gained much attention in the context of intellectual property rights protection, a much wider range of applications can benefit from this technology. This paper investigates the different areas of applications and their specific requirements with respect to watermarking technology. Both watermarking in linear and compressed domain are contrasted in their concepts and properties. For both cases examples for the underlying technology and recent technological advances are described.

A short glossary of watermarking terms is given in Sect. 2 as a prerequisite to later discussions on the requirements of different applications of watermarking. In Sections 3 and 4 PCM watermarking and bitstream watermarking systems are discussed, respectively. These sections also describe the current status for an example system and give an update on issues of sound quality, detection performance and other improvements compared to former publications [2, 3].

Finally, in Sect.5 application areas for watermarking are discussed. This includes "backward compatible channel" applications, broadcasting applications and applications in the domain of Intellectual Property Protection (IPP). For all systems an overview about their specific requirements and features is given.

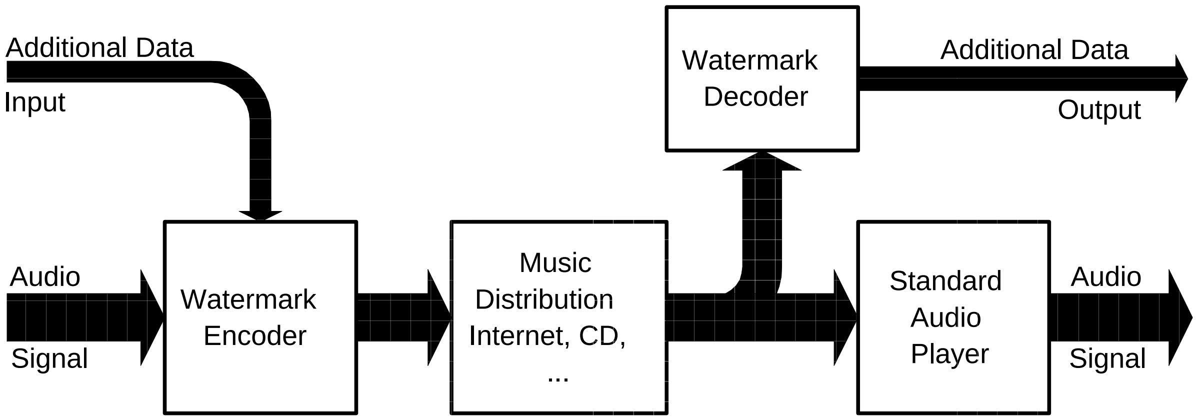

Figure 1: Watermarking as a compatible data channel

2 Watermarking Glossary

The following terms are commonly used to describe and/or classify different watermarking schemes. As will be discussed later in this paper the relative importance of these aspects can be established only in the context of the respective application domain.

- **Perceptual Transparency/Inaudibility**
  Often inaudibility of the watermark is the most desired feature in audio watermarking. It should be clear, however, that the notion of inaudibility always relates to a certain target sound quality. Consider a short wave radio transmission with its very low sound quality. An adequate watermark does not need to fulfill CD listening

tests. In other cases, e.g. prelistening of pay-audio material the audibility of the watermark might even be intended. Thus, absolute watermark inaudibility is not required in all cases. A good watermark embedder should use knowledge of the quality delivered by a particular transmission channel.

- **Robustness/tamper resistance**
  Robustness of watermarking systems, like inaudibility, is often considered to be a very important issue. It refers to the idea that intentional, unintentional removal or distortion of the watermark detection should only be possible by accepting a clear degradation of the audio signal quality.

- **Watermark data rate**
  Watermark bitrate denotes the number of bits/s that can be transmitted by the system and depends on the underlying technology. While higher data rates are always desirable, there are clear principal bounds to what a restricted hidden communication channel can deliver. Typical spread spectrum systems offer bitrates between a few to a few hundred bits/s.

- **Operation domain**
  Operation domain denotes the domain, uncompressed or compressed, of the input signal processed by the watermark embedder. Accordingly, the terms *PCM Watermarking* and *Bitstream Watermarking* are used to describe these systems. Depending on the application, either of both system types may be required.

- **Interoperability**
  For reasons of consistency it may be desirable to require interoperability between the watermarking formats of PCM and bitstream watermarking schemes (see Fig. 2). In this context, interoperability ensures that the same watermark extractor can be used for both the bitstream and the PCM watermark embedding scheme, regardless of the domain of embedding. In order to achieve this, the same watermark signal representation must be used in both systems.

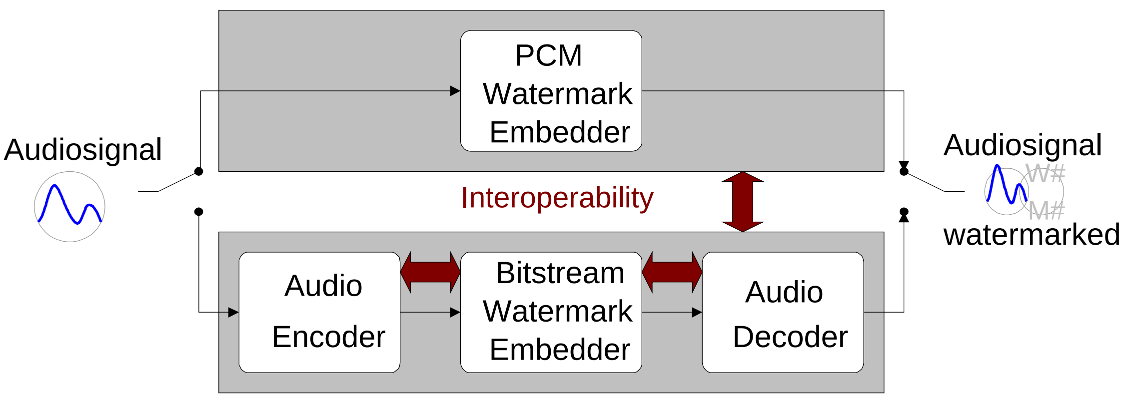

Figure 2: Interoperability

- **Complexity**
  Both the complexity of the watermark embedding and the watermark extraction process are of concern for practical use. There exist various tradeoffs between complexity and other system properties, e.g. ”complexity vs. reliability” within the watermark extractor or “complexity vs. audibility” in the watermark embedder. Again, the application dictates what degree of complexity can be tolerated.

- **Blind vs. non-blind watermark detection**
  Most watermarking systems proposed today are capable of recovering the watermark data from the watermarked signal without requiring access to the unwatermarked original. This is called *public*, *oblivious* or *blind* watermarking. This scenario forces the watermark extractor to cope with the cover signal, e.g. the audio signal, and leads to hard detection conditions. Detection performance can, however, be greatly enhanced if both the watermarked signal and its original are available. This is in fact possible in some applications, allowing *non-blind* watermarking detection.

Most of the above mentioned terms depend on the design or system inherent properties of a particular watermarking scheme. However, the properties *inaudibility*, *robustness* and *data rate* form a tradeoff that is applicable to every watermarking system. This tradeoff is shown in Fig. 3. Within this triangle the “mode of operation” of a particular watermarking system can be set. For example a high data rate system may enhance its rate by lowering the robustness at the same moment. The same applies for a perfectly inaudible watermarking system that will never achieve the degree of robustness of a less inaudible system. For spread spectrum systems the “data rate vs. inaudibility” tradeoff does not exist directly, but it can be achieved by a correct adjustment of robustness.

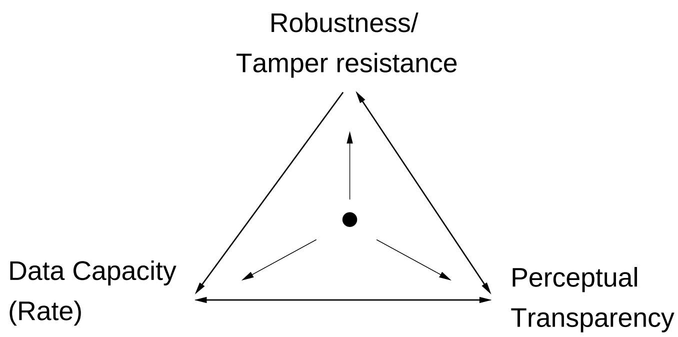

Figure 3: Tradeoff between robustness, rate and perceptual transparency.

It is obvious from Fig. 3 that different applications with different properties should choose an appropriate operation point within the limits of the watermarking system. For example an IPP application may want to have high robustness at the cost of a lower data rate, whereas broadcast applications may want to achieve higher rate at the cost of robustness (and/or audibility).

The conclusion of these considerations is that an usable watermarking system should offer some flexibility that allows it to match the various requirements of different applications.

3 PCM Watermarking

The term PCM audio watermarking refers to the embedding of watermarks into uncompressed ("linear") audio signals. Various schemes exist to perform this task, such as *echo Hiding* [4, 5], direct modification of time domain signals [6], narrow band systems [7] and the large group of spread spectrum based systems [8, 9, 10, 11, 2] which are described in more detail below.

3.1 Spread Spectrum Approach

The idea of spread spectrum modulation originally had its roots in the area of secure communications where a robust reception of RF signals has to be achieved even under adverse channel conditions, such as intentional interference from other transmitting stations. Moreover, spread spectrum modulation supports the concept of a broadband modulated signal which is "buried" under other signal components and in this way is hard to detect without a-priori knowledge about the modulation parameters [12]. Both properties make spread spectrum technology an ideal candidate for application in digital watermarking.

A block diagram of a typical spread spectrum watermarking system is shown in Fig. 4. In such a scheme masking thresholds are used in order to hide a watermark signal in very much the same way quantization noise is hidden in a perceptual coder. While the rate of the watermark data signal is small (typically in the range of a few bits per second) the data signal is expanded in bandwidth by the operation of spreading [13, 14, 15]. Typical bandwidths after spreading are 12 kHz to 18 kHz.

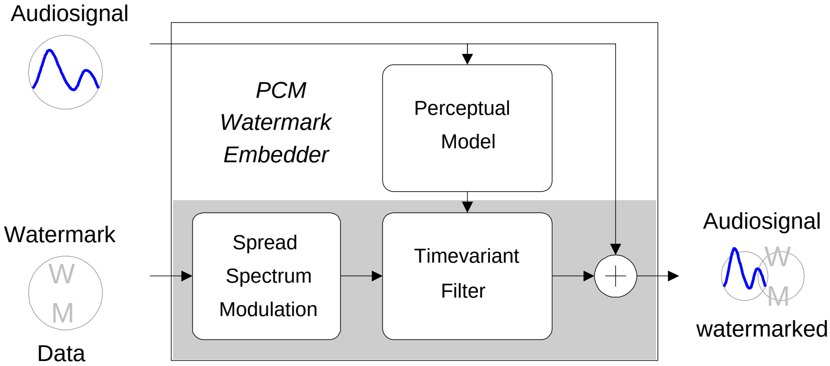

Figure 4: Block diagram of PCM watermark embedder

Furthermore a perceptual model is used to compute an estimate of the so-called masking thresholds. A masking threshold denotes the energy of a signal that is just masked by the audio signal.

The masking thresholds are used by a time-variant filter in order to shape the energy distribution of the spread spectrum data signal according to the masking thresholds. This is accomplished by applying a specific attenuation to each frequency partition of the spread spectrum modulated data signal. After performing the shaping operation the spectral energy distribution of the data signal over frequency follows the masking threshold of the audio signal and in this way ensures inaudibility of the watermarking signal after embedding.

3.2 Current Status

In order to give an impression of the current capabilities of spread spectrum based audio watermarking systems, this section presents some of the current key performance figures for an example system based on earlier work in this area [2]. Keeping in mind the inherent tradeoffs between the basic system parameters (i.e. robustness, data capacity and data rate), this includes both results from bit error measurements and subjective listening tests at a certain data rate (see Tab. 1).

The quality of the watermark transmission was evaluated with a bit-error-rate measurement. The test was carried out using a large set of sound items of all genres. More than 1 million watermark data bits were run through the system in order to get sufficient statistics for the measurement. The resulting raw bit-error-rates (10^{-3}...10^{-4}) are low enough to satisfy the needs of most applications but can also be regarded as a good starting point for the use of channel coding techniques.

The listening test results were gathered in accordance with ITU test specification BS.1116 test [16, 17] with seven experienced listeners using critical test items[1]. A difference grade of "-1" corresponds to a degradation of audio quality which is deemed "perceptible but not annoying". As can be seen from Fig. 5, the watermarking process delivers transparent audio quality for the majority of the test items. Marginal impairments are observed for speech signals.

Property	Value
Operation domain	linear (PCM)
Type of Watermark	blind, i.e. no use of original signal for decoding
Watermark Bitrate	11.7 bits/s
Complexity/Ch. @48 kHz	$\approx$ 6 times faster than realtime on PII@400 Mhz
Average Raw Bit-Error-Rate	10^{-3}...10^{-4}
Inaudibility	see listening test Fig. 5

Table 1: Key figures of PCM watermarking system.

[1]These items represent a corpus of audio material which contains excerpts from single instruments, multiple instruments, complex sound sources and speech and have been used extensively for assessment of subjective sound quality in the MPEG-4 audio development process.

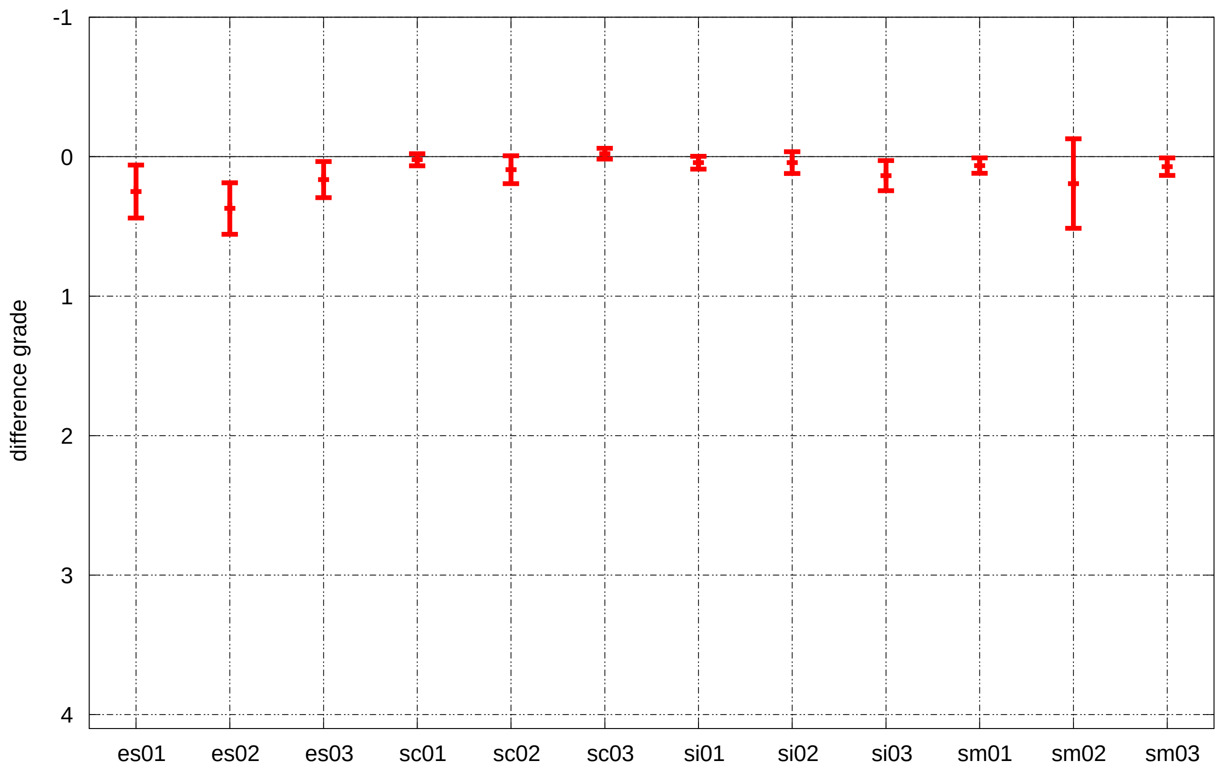

Figure 5: Listening test results of PCM watermarked test items.

4 Bitstream Watermarking

The term *bitstream watermarking* denotes the fact that embedding of watermarks is carried out directly in the bitstream domain without full decompression and re-encoding of the signal. Since this requires usage of technology components from both watermarking and source coding, the number of available systems for bitstream watermarking is substantially smaller than the number of PCM watermarking systems offered today.

The demand for bitstream watermarking is motivated by the fact that compression technology is in wide spread use today, accommodating both efficient storage and delivery of audiovisual content over global networks, such as the Internet. Consequently, content databases are based on compressed data formats. If watermarks must be inserted into content prior to its distribution (again in compressed format), direct embedding of watermarks into compressed data is required.

4.1 Principles of Bitstream Watermarking

In principle, embedding of watermarks into existing bitstreams can be achieved by subsequent decoding, PCM watermarking and re-encoding of the signal (see Fig. 6). A true bitstream watermarking scheme will, however, operate as a "shortcut" and combine the relevant operations of this sequence of steps.

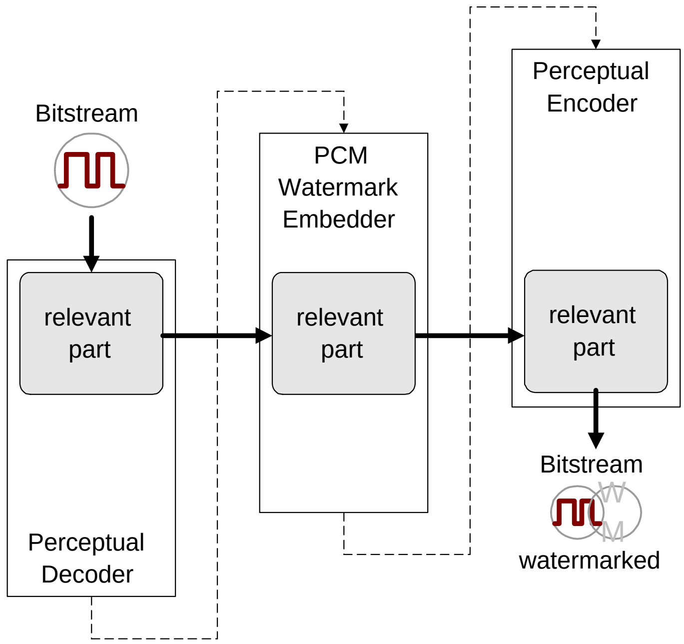

Figure 6: Basic idea of bitstream watermark embedding.

As a consequence, there are a number of compelling benefits which bitstream watermarking schemes are able to offer within the appropriate application scenarios:

- **Improved sound quality by avoiding cascaded encoding/decoding**
  Using a true bitstream watermark embedder will result in clear improvements in sound quality compared to the naive decoding–watermarking–encoding scenario mentioned above since the quality loss by repeated encoding/decoding of audio material ("cascaded coding", "tandem coding") is avoided.

- **Control over coder distortion vs. watermark distortion**
  The fact that the bitstream watermarking takes place *after* the perceptual encoding step opens up interesting possibilities for achieving a better overall sound quality. More specifically, the watermark process can be aware of the distortion already incurred in the course of the perceptual encoding process and control its embedding parameters so as to achieve optimum sound quality for the combined encoding/watermarking process.

- **Robustness**
  Since the result of the bitstream watermarking process is already in compressed form, there is no need to weaken the embedded watermark by a subsequent encoding step.

- **Low computational complexity**
  Due to the fact that bitstream watermarking implements a "shortcut" operation within the coded domain, very efficient implementations can be achieved which are suitable for real-time on-the-fly watermarking of content as it is streamed by the server for distribution.

Basically, the different schemes described in the context of PCM watermarking (e.g. echo hiding, spread spectrum watermarking) can also be implemented as bitstream watermarking. In the following section the current status of bitstream watermarking is illustrated by example of an available system [3], which is based on the MPEG-2 Advanced Audio Coding (AAC) codec [18] and spread spectrum technology. Implementations for other codecs like MPEG-1/2 Layer-3 (aka MP3) using the same concepts are currently under development.

4.2 Bitstream Watermarking for MPEG-2 AAC

A block diagram of a generic system for bitstream watermarking is shown in Fig. 7. Basically the system decodes the bitstream until a spectral representation of the input audio signal is retrieved. After modulation of the watermark data into a watermark signal this signal is converted into the spectral representation of the coder by means of an analysis filterbank. A spectral weighting stage shapes the watermark signal with respect to the estimated thresholds. Both signals, the shaped watermark and the audio signal are added, quantized, entropy-coded and multiplexed into the output bitstream containing the watermark.

The system described in [3] implements a bitstream watermarking scheme for MPEG-2 Advanced Audio Coding (AAC) and gives first results for a combination of a monophonic variable rate AAC coder and the bitstream watermarking. A noticeable detail of the approach chosen is the way of obtaining masking thresholds to be used by the watermarking system: In order to achieve both a computationally inexpensive and accurate estimation of these important parameters, the masking thresholds as calculated in the perceptual coder are transmitted to the watermark embedder within a special "hint" field in the bitstream in a compatible way and may be stripped off after usage by the watermark embedder. Similarly, information about the distortion already incurred by the encoding process could be streamed to facilitate a joint optimization of encoding and watermarking.

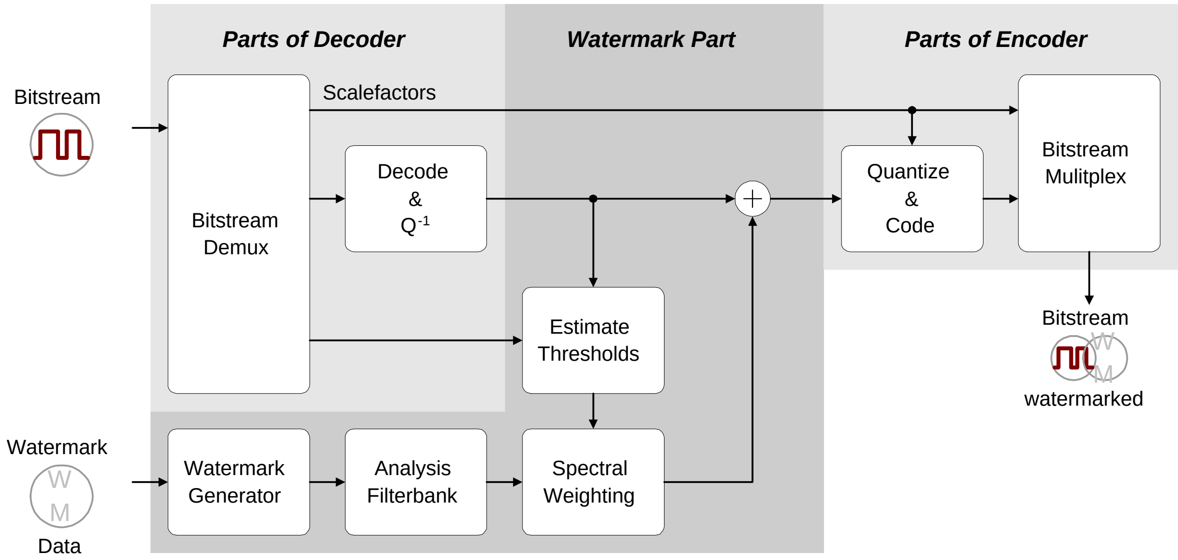

Figure 7: Block diagram of bitstream watermark embedder.

4.3 Current Status

Since the publication of [3], the bitstream watermarking system underwent the following enhancements:

- **Constant Bitrate Coding**
  The watermark embedding scheme was extended to handle input from a constant rate coder rather a variable rate coder always running at masking threshold. While variable rate coding will not present a problem for storage based applications, use of compression with constant-rate transmission channels (e.g. broadcasting channels or ISDN networks) will require a constant-rate type encoding. As a consequence, the embedding algorithm is now confronted with effects like overcoding or undercoding[2] which result from encoding signal portions of different bitrate demand within a fixed bit budget.

- **Support for Coding Tools**
  The watermarking embedder has been extended to support the additional coding modes provided by the so-called "coding tools" as described in [18], including e.g. Temporal Noise Shaping (TNS)) [19] and Mid/Side (M/S) joint stereo coding [20].

[2]over/under-coding: quantization step smaller/larger than required by masking model

The performance evaluation of the bitstream watermarking scheme was carried out with the same methodology used for the PCM watermarking tests in Sect. 3.2. Again the key performance figures of the system are summarized in Tab. 2.

As can be seen from the listening test results in Fig. 8, the confidence intervals of the non-watermarked and the watermarked bitstreams overlap for the majority of the test items, indicating that there is no statistically significant difference in subjective quality for both signals. For none of the remaining items, the resulting subjective quality exceeds substantially a difference grade of "1" (i.e. "degradation is perceptible but not annoying").

Property	Value
Operation domain	compressed (MPEG-2 AAC)
Type of Watermark	blind, i.e. no original for decoding
Watermark Bitrate	11.7 bits/s
Complexity/Ch. @48 kHz	≈ 5 times (faster) realtime on PII@400 Mhz
Average Raw Bit-Error-Rate	$10^{-2} \ldots 10^{-3}$
Inudibility	see listening test Fig. 8

Table 2: Key figures of bitstream watermarking system.

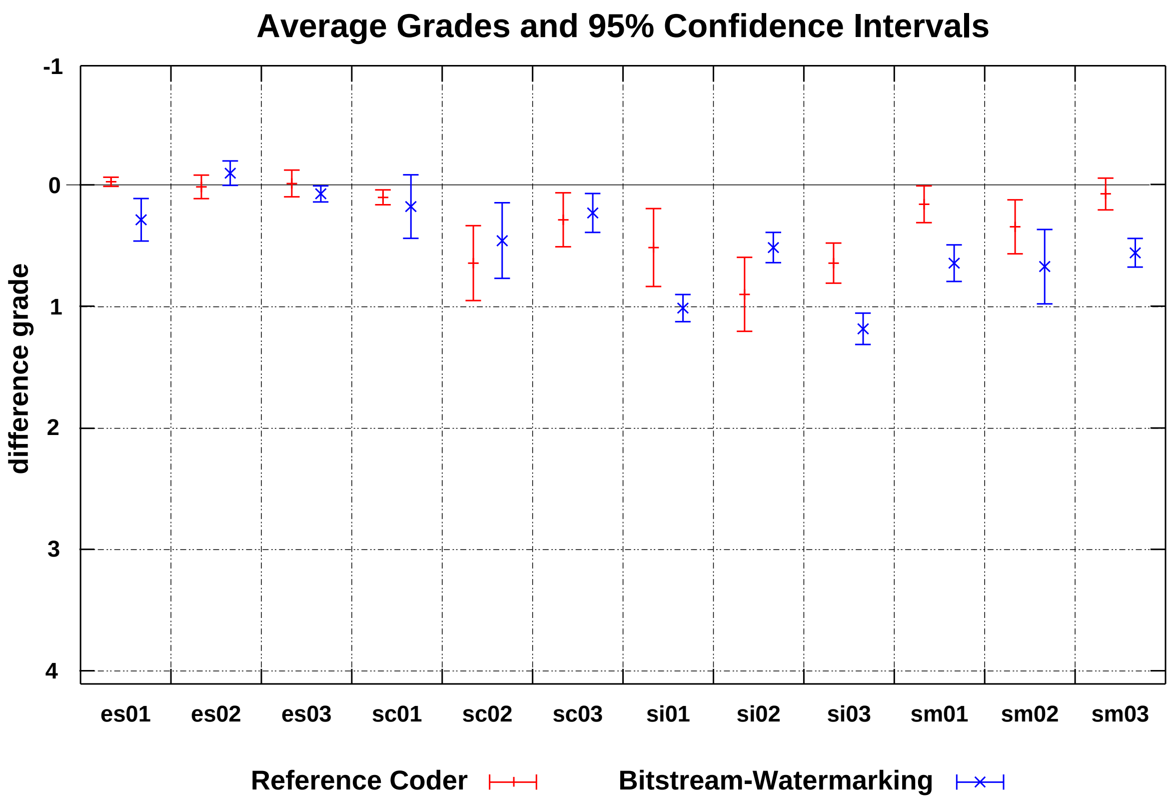

Figure 8: Listening test results of watermarked bitstreams compared to unwatermarked bitstreams.

5 Application Areas

Basically watermarking algorithms provide a data transmission channel that can be used in existing distribution channels. This data transmission is compatible in the sense that every existing channel that is able to carry music also is able to carry watermarked music. Hence watermarking can be utilized in a wide field of applications. Each of these areas of application imposes specific requirements on the properties of the watermarking system. In this section we will discuss some of the conceivable applications for watermarking and their specifics with respect to the basic characteristics introduced in Sect. 2.

5.1 Compatible Transmission of Meta Data

Given the fact that watermarking aims at a compatible hidden in-band transmission of data, it is easy to conceive that there is a large number of ideas about how to make use of this capability. In particular, the ever-increasing amount of available audiovisual content has stimulated the need for descriptive annotations of such material to enable efficient handling, such as search and retrieval. So-called *Meta Data* ("data about data") may e.g. in the case of music material contain the title, composer, player, soloist, genre as descriptive information associated with the actual content.

The following considerations may be helpful in understanding the requirements for watermarking as a means for the transmission of meta data:

- **Robustness**
  Transmission channels may include e.g. broadcasting, CD, Internet distribution in both compressed or uncompressed form. Usually, the use of watermarking for transmission of meta data will not require extreme requirements with respect to robustness since the additional data represents some desirable "added value" from the user's point of view because it enables additional services. If the watermark and thus the meta data is striped out or destroyed this is usually done at one's own disadvantage.

- **Sound Quality**
  Clearly, the sound quality of watermarked music must be very high for this application, because users are unlikely to accept the benefits of associated data if they come at the expense of sound quality.

- **Complexity**
  In terms of watermark embedder complexity, usually no substantial constraints have to be met because the number of watermark embedders is low compared to the number of watermark extractors at the user/client side. Moreover, the embedder may be a professional device while the watermark extractor must be sufficiently

low in complexity to be part of a reasonably-priced consumer device. The decoder algorithm should be easily implementable in both software and hardware.

- **Data Rate**
  The data rate for this application should be as high as possible to carry a maximum amount of additional data along with the audio. In spread spectrum based watermarking systems a tradeoff between watermark rate and robustness can be achieved e.g. by a proper parameterization of the spread spectrum modulation stage.

- **Interoperability**
  Interoperability between watermark embedding in the uncompressed domain and the compressed domain is required to enable use of a single extractor at the client side. Consider on one hand embedding of meta data during the mastering process in a studio and on the other hand embedding of meta data during perceptual coding of the same signal. Both kinds of meta data should be retrievable by the same consumer watermark extractor.

- **Detection**
  The original audio signal (without watermark) is typically not available for extracting watermarks. Consequently, a blind detection of the watermark is required.

5.2 Broadcasting

A variety of applications for audio watermarking are in the field of broadcasting, most of which are based on the scenario of compatible transmission of some type of data as described in the previous section. This section extends these ideas by considering some more broadcasting specific application examples.

Currently, additional data services for analog broadcasting can be made available to the end user by using the Radio Data System (RDS)[3]. These services are, however, only available in the FM band and require the radio receiver to be internally equipped with an RDS decoder. Watermarking can be used to provide a similar service which does not depend on a particular transmission band and the existence of a decoder which is integrated into the radio receiver. Due to the fact that the additional information is carried within the audible frequency range, the data signal is carried on *every* broadcast channel and simply can be decoded by adding a (hardware) watermark extractor to the particular receiver. Possible applications for broadcasting are:

- **Program Type/Broadcast Station Identification**
  This allows to automatically discriminate different transmitter stations or program types by embedding a unique watermark into the broadcast signal. Furthermore it is conceivable to transmit strings containing radio station name or program type,

[3] see also http://www.rds.org.uk/

like available via RDS these days. The decoder would be implemented as a hardware device connected to the receiver's audio output terminal or even simply "listening" to the played audio via an internal microphone. The benefit of the latter approach is that sender or program type identification is achieved regardless of the kind of receiver (equipped with audio output or not; SW/FM/AM/DAB).

- **Advertising Research**
  Advertising research for audio broadcasting is currently done by asking test persons or letting them write down what they listened to during the day. This procedure is of course very error-prone. Embedding watermarks into advertising spots can solve this problem. Each advertising spot is watermarked with a different ID number. A group of selected test persons is equipped with a (preferable portable) watermark extractor. This device listens to the radio program and stores the decoded ID along with a time stamp in its internal memory. After finishing the test, the devices are collected and read out, to analyze the collected data.

- **Broadcast Coverage Research**
  Another application is broadcast coverage research. Therefore test stations equipped with watermark extractors are placed at the boundaries of the transmitter coverage area, looking for a particular sender ID and storing that information. In this way transmission breakdowns can be detected safely.

As pointed out in Sect. 2, the sound quality of the particular medium (FM, AM, SW, DAB, etc.) is important to determine the watermark embedding strength. For example, in FM systems watermarks must be embedded more carefully than in AM/SW systems, because the latter offer much lower intrinsic quality. On the other hand, robustness of the system should be set up to survive the conditions of the particular broadcast medium. Band limiting, compression and other signal processing typically done during broadcasting must be survived by the watermark signal.

5.3 Intellectual Property Protection

Intellectual property protection (IPP) is often considered as the main (and occasionally even only) application of watermarking. While this is a debatable statement in light of the issues discussed so far, it is certainly true that watermarking can provide important contributions to the field of intellectual property protection within a more extensive security framework:

- **Proof of Ownership**
  Proving ownership of music will become an important issue for Internet music delivery. An example is used to illustrate the mechanism.
  Assume A produces a piece of music and embeds a watermark. The original never

leaves the studio, instead the watermarked signal is distributed. Assume further, B claims to be the originator of the music. To validate the mutual claims each party is asked to take the "original" of the other party and to try to decode a watermark. If B takes the original from A, no watermark can be decoded, because there is no watermark contained. This does not yet allow for immediate conclusions. However, if A is asked to extract a watermark from B's "original" (which was watermarked by A before distribution) he will decode his watermark. Hence B does not hold an original, because there is a watermark in it. So, actually A cannot prove that he is the legal owner, but he can prove that B is not. This should be sufficient for practical purposes.

- **Access Control**
  Access control is another application that can be covered by watermarking. The principle is to embed a watermark that is used as a trigger, which is used to decide whether content is allowed to be played or not. This application scenario, however, has the drawback that the user is both not interested in the watermark and is in the possession of a watermark extractor (which is part of his playback device). Consequently, there is a high probability that such a watermarking system will be attacked and successfully broken over time, making all investments in watermark extractor hardware in sold consumer equipment useless.

- **Tracing Illegal Copies**
  In Fig. 9 a conceptual model of a 'pay audio' system is shown. The idea is to embed a personalized watermark into the compressed audio signal during delivery using bitstream watermarking. If the customer transfers the bitstream into the illegal world (e.g. his personal web site) he must be aware that a watermark identifying himself is contained in the bitstream. Hence, he can be made responsible if the signal is found outside the legal domain. The benefit of watermarking compared to cryptographic methods in this context is that also the decompressed audio signal contains the watermark – even in an analog representation. So simply decompressing and coding the signal again is no way to get rid of the watermark.

For the above mentioned applications the audio quality of watermarked material should be high to be accepted by providers and consumers.

A convenient embedder for a system shown in Fig. 9 operates in the compressed domain due to the performance gain offered by bitstream watermarking. For proving ownership, however, watermark embedding is done during the mastering process in linear domain.

In addition, the robustness requirements are rather high for these applications, because intentional tampering of watermarks must be considered. This leads to relatively low data rates in the order of a few bits/sec. On the other hand, the original sound file is available for the purpose of tracing illegal copies which offers highly improved detection performance by non-blind detection. Finally, interoperability must be considered only in scenarios where compressed as well as uncompressed signals are watermarked.

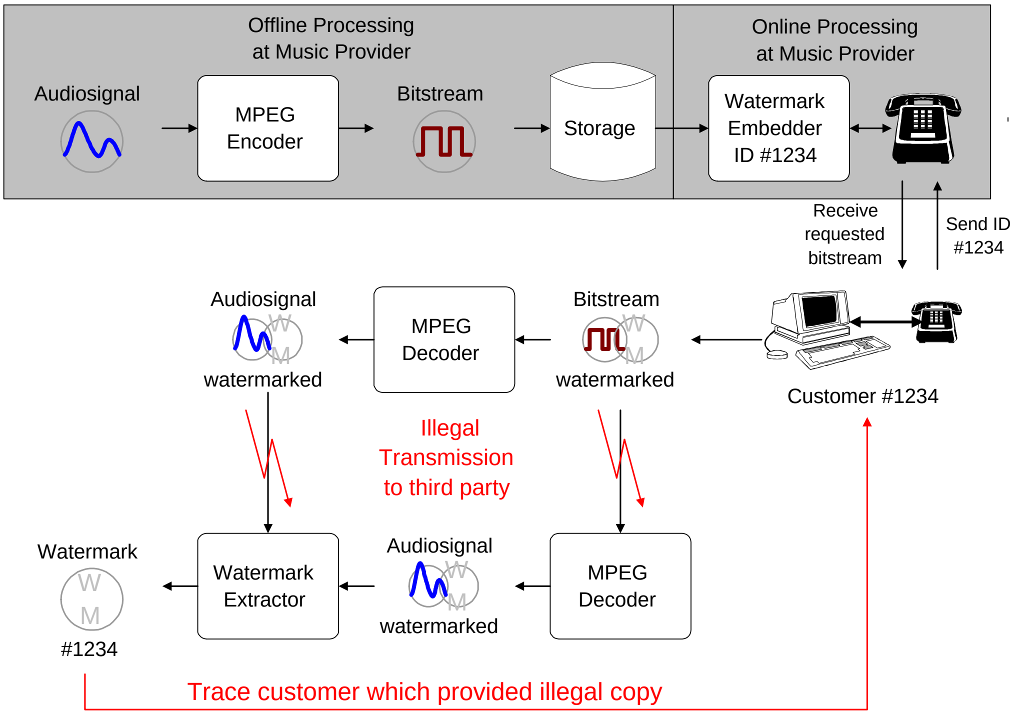

Figure 9: Example for a pay audio system capable of tracing back to illegal users.

5.4 Summary

In the previous sections it has been illustrated that different applications demand different properties of a watermarking system. A general purpose watermarking system therefore should offer a high degree of flexibility to fullfil these requirements. In order to summarize the above discussion Tab. 3 gives a compact overview of the different requirements.

Property	Data Transmission/ Broadcasting	IPP application forensic proof	IPP application access control
Audio Quality	high³	high³	high²
Embedding Domain	Bitstream/PCM	Bitstream/PCM	Bitstream/PCM
Robustness	medium¹	high³	high²
Embedder Complexity	high¹	low²	high¹
Extractor Complexity	low²	high¹	low¹
Watermark Data Rate	medium-high²	low³	low³
Detection Mode	blind	non-blind	blind

¹) can be ²) should be ³) must be

Table 3: Comparison of requirements of different watermarking applications.

6 Conclusions

In this paper, we briefly reviewed the current state-of-the-art in audio watermarking and discussed some of the key terms that are relevant in this context. Understanding these terms is essential for an appreciation of the specific tradeoffs that need to be made with respect to specific applications of watermarking technology.

Based on these considerations, two watermarking approaches, PCM watermarking and bitstream watermarking, have been presented. While PCM watermarking technology is already widely available in the marketplace, bitstream watermarking is a more recent development combining components from both watermarking and source coding technology. The latter approach enables efficient use of watermarking in the context of compressed storage and distribution of content. For both types of embedding the current technological status was illustrated in terms of description, sound quality and detection performance for a selected example.

Different application fields for watermarking technology were discussed: Firstly the "compatible transmission of meta data" allows to transmit additional data, like meta data, on every channel that can transport music and in this way enables additional services. An other application area is broadcasting which allows to automate tasks like broadcast station identification, advertising research, etc. Finally, applications for the protection of intellectual property rights and their special demands were discussed.

7 Acknowledgments

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