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– the state of the art and results of EBU tests

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Research & Development
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Although audio watermarking is often thought of as a new technology, many of the current techniques have been known for decades. Several of these are described.

The potential applications of audio watermarking are numerous, including the obvious copy protection and content identification functions. Some examples of applications and the implications for location of watermark embedders and detectors, are presented. The balance between payload capacity and robustness for different applications is assessed.

The EBU has recently completed tests of the robustness and subjective quality of state-of-the-art audio watermarking systems. The test methods are described, including the attacks to which the watermarks were subjected, and the subjective test method (a combination of BS.1116 and a forced choice). The results of the tests are presented.

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Andrew Mason

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What is watermarking

Watermarking has been used for many years for the authentication of banknotes, but in the context of audio (and video) signals, a watermark is an imperceptible modification to the signal that can be detected on request, and that can convey hidden data. Watermarking should not be confused with on-screen logos, or with content analysis and recognition (also known as "fingerprinting"), or with scrambling.

Watermarks can be robust or fragile, can convey a lot of hidden data, or a little. The properties of a watermark depend on the application for which it is intended. In general though, watermarking provides a secret, indelible mark, embedded in the signal itself, that can survive conversions from one medium to another.

The idea of hidden data channels in audio signals has been around for some years. BBC Research Reports from over 30 years ago [1,2] describe investigations into a wide variety of techniques. This work was constrained somewhat by the technology available at the time. More recently, the availability of digital signal processing techniques, has made the work much easier. Many papers have now been published, widely cited ones being by Bender [3], Cox [4], Boney[5]. Some learned journals have dedicated whole issues to the subject of data hiding and security [6,7].

Why use watermarking

The advent of digital audio media (CD, MD, DVD, MP3) and the ability easily to transfer content without loss of quality have caused a resurgence of interest. However, there are several applications of watermarking beyond copy protection. They can be broadly classified into two types: identification and authentication. Identification associates the signal with some descriptive information. The watermark could carry the information, or it could carry an identification number pointing to information in a database elsewhere. Authentication establishes whether the signal is what it claims to be or not. The interest for broadcasters is almost entirely focused on applications of identification[8].

Figure 1, below, shows several different points in the broadcast chain where watermarks might be embedded for different applications.

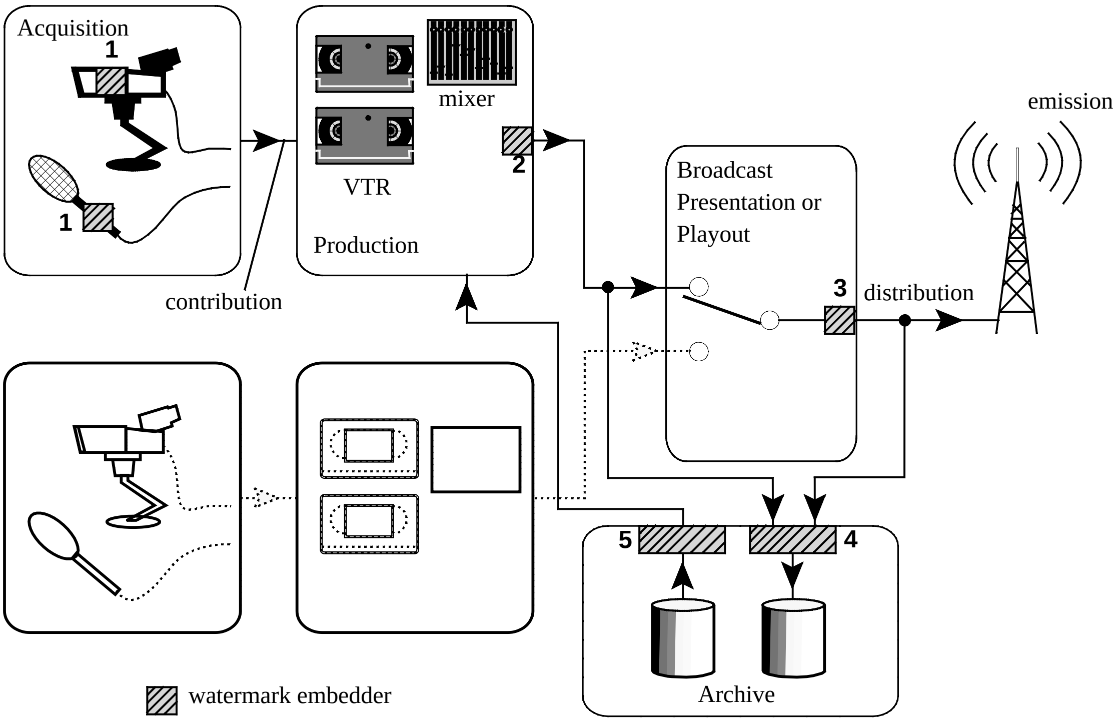

Figure 1 : Watermark embedding points in broadcast applications

At point 1, each camera or microphone could embed an identifier unique to itself, conveying time, place, equipment serial number, and so on;

At point 2, each finished programme could have a programme identifier added to it;

At point 3, each broadcast network could be identified, including time and date of transmission;

At point 4, as each programme enters the archive its catalogue number could be added;

At point 5, as requests for programmes from the archive are fulfilled, a watermark to identify the recipient could be added.

There are corresponding different points where watermark detection might be done, again, depending on the application. These are shown in Figure 2, below.

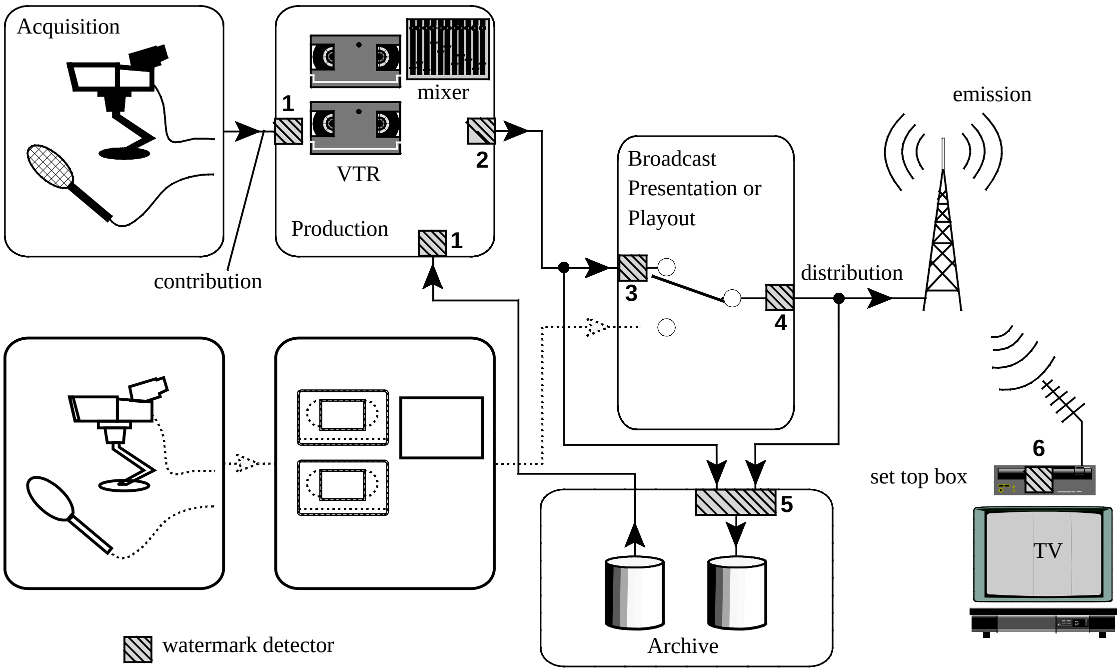

Figure 2 : Watermark detection points in broadcast applications

At point 1, the input to production, the identity of material coming in that will be used in a programme can be established. Because of the short length of some clips, and the large amount of data that might be required, the payload capacity requirement is large. However, the robustness requirement is slight;

At point 2, the output of production the ability to identify automatically programme material, and the rights associated with its use, can be very useful. The payload capacity requirement is again high, but robustness still slight, provided high quality is maintained;

At point 3, in presentations, being able to identify signal sources is very valuable in order to ensure that the right programme feed is routed to the right network. Payload capacity is less and the robustness requirement should still be slight, unless poor quality connections are used;

At point 4, as programmes are sent to the network, automatic logging of content could be used to ensure that rights usage is accurately recorded. The payload capacity is high, but robustness depends again on the programme production and contribution processes;

At point 5, information can automatically be linked from production to archive by detection of watermarks that point to the production metadata. Payload capacity depends on whether there is a need only to identify complete programmes, or to identify short segments within programmes;

At point 6, the whole world, monitoring can be performed to detect whether programme material is being broadcast as it should be. There is a need to know that content that should be broadcast has been broadcast, and there is a need to know that content that should not be broadcast has not been broadcast. Audience monitoring can also be done at this point to find out how many people watched a particular broadcast. The payload capacity can be high or low, depending on the length of segment of interested. Robustness generally needs to be high.

An information channel within the audio or video content can be used to convey all kinds of data to enable a wide variety of consumer applications. Web URLs, telephone numbers, automated event triggers, are examples things that could be sent, invisibly or inaudibly, through an existing audio or video circuit.

However, as mentioned earlier, one of the highest profile applications at the moment is that of copy protection (or copy prevention). A watermark can be used to carry information about whether a particular signal is able to be recorded, or re-distributed, or not. The payload capacity requirement is relatively low, but the robustness requirement is extremely difficult, if not impossible, to achieve.

All the above examples are of identification. Authentication also has a place, for example to ensure that web site content has not been tampered with (on the original site, or on other sites where it is being used with, or without, permission). Authentication is beyond the scope of this paper.

Some techniques for audio watermarking

Space here does not permit a detailed description of all the techniques available at present, so a brief overview of some of the more common ones is all that is included. See the references for more information and more references.

Least-significant bit modification

In a 24-bit, or even a 16-bit, linear digital audio signal, modifications to the least significant bit are almost always inaudible, if done with a little consideration. If used as a data channel this can provide around 90bit/s - enough for another (compressed) audio signal. An example of this technique was standardised for conveying MPEG coder control data in the ATLANTIC project[9,10]. Although the data capacity is high and the audibility low, the hidden data can be destroyed by even small alterations to the signal.

Signalling in defined frequency bands

Data can be embedded by adding low-level tones to the signal. See Figure 3. Here advantage can be taken of masking provided by the host signal. The figure shows two tones hidden in the mid-part of the audio spectrum, masked by the presence of another signal. In another application, the tones could be carried high-up in the spectrum, above 20kHz for example. Here a wider bandwidth might be available, the tones are likely to be inaudible, but might be removed by low-pass filtering.

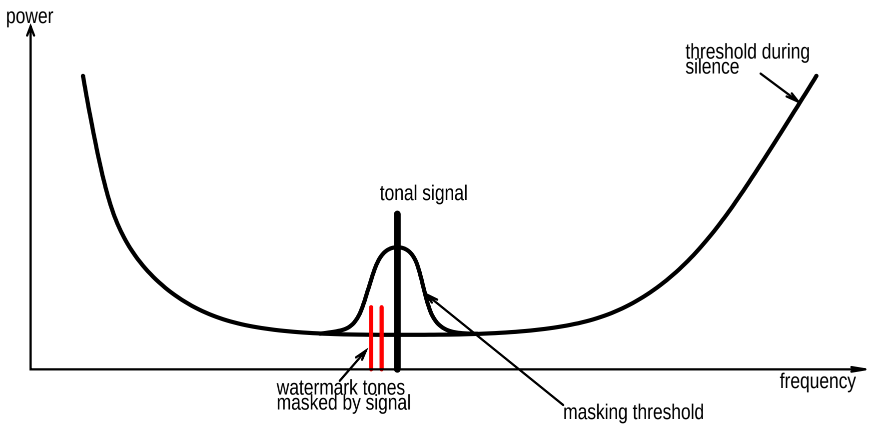

Figure 3 : Addition of low-level tones

Spread spectrum modulation

Rather than adding tones to the signal, data can be carried by spreading it across a wide spectral band. Here the data might still be recoverable even if some parts of the spectrum are removed. The added noise can be generated by multiplying a pesudo-random number sequence by each of the bits in the stream of data to be embedded. To minimise audibility the sequences can be filtered according to a psycho-acoustic model. This is shown in Figure 4.

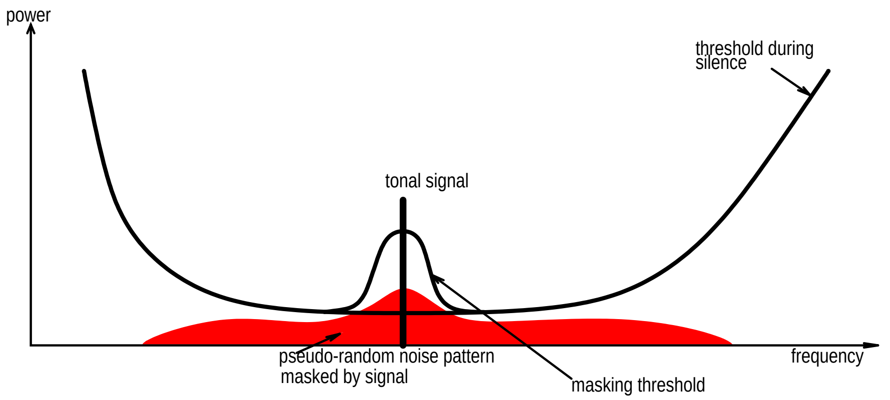

Figure 4 : Addition of spread spectrum signal

Echo hiding

Another way of conveying data in a signal is by adding low-level echoes of the signal to itself. The time-delays and relative amplitudes need to be chosen carefully to avoid undue audibility. Data can be conveyed by adding echoes with different time intervals. See Figure 5.

Although investigated by Hill [1] it has been the advances in digital signal processing hardware that have rendered this a practical technique: detection involves calculating the auto-correlation of the cepstrum of the signal.

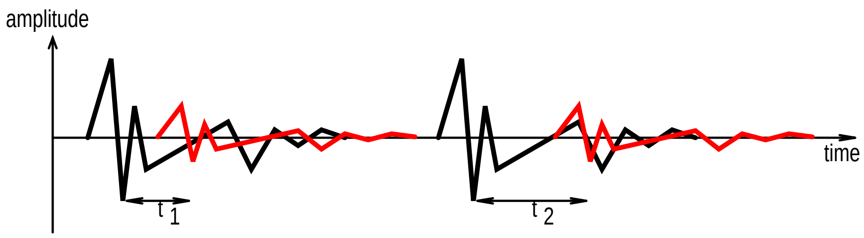

Figure 5 : Addition of low-level echoes

There are, of course, other techniques. Whether any are useful for a particular application depends on the fundamental characteristics of perceptibility, robustness, and data capacity.

EBU testing of watermarking systems

The EBU has been actively involved in watermarking, for video and audio, for several years. A technical project group, N/WTM, was formed to evaluate the application of watermarking signals transmitted over the Eurovision network for purposes of copyright protection. Thorough tests were conducted on video watermarking systems in 2000 [11]. Audio watermarking tests followed and have recently been completed. The process was lengthy, starting in June 2001, finishing in July 2003. In summary, a list of technical requirements was made; calls for systems were issued; systems were received and tested. Several members of the EBU Project Group B/AIM (Audio In Multimedia) were involved in the test process, in particular IRT, Polish TV, and France Télécom, as well as the BBC.

EBU audio watermarking system requirements

Perceptibility

The audio watermarks were required to be inaudible in studio listening conditions. This would be assessed by subjective tests according to ITU-R BS.1116 [12]. However, because it was hoped that the standard of systems submitted would be high, such that any impairments to the audio signal would not be revealed by BS.1116 tests, an addition was made to the test method used. Subjects were required to indicate which of the two signals to be graded (the hidden reference and the watermarked signal) they thought was watermarked, *even if they would have indicated that the effect was imperceptible*. This is called a forced choice.

The normal BS.1116 selection panel process was used to find the set of items to be used in the test. These are listed in Table 1.

Table 1: Signals used in test sessions, with watermark at normal level

Test item number	Item type (and source)
4	xylophone (EBU SQAM, track 41)
8	flute (EBU SQAM, track 13)
9	glockenspiel (EBU SQAM, track 35)
13	triangle (EBU SQAM, track 32)
16	violin (EBU SQAM, track 8)
27	harpsichord (EBU SQAM, track 40)
31	English male speech (EBU SQAM, track 49)
34	German male speech (EBU SQAM, track 54)
36	wind ensemble (EBU SQAM, track 36)
39	Tennis (BBC)

A small number of other items was used, with the watermark at boosted levels. Boosted level watermarks were created in order to train listeners, and to provide something in the test that would be detectable by ear. Only one of the systems submitted provided the means to do this, as requested in the call. Unfortunately this system was not included in the listening tests. The other systems did not provide a means, so difference signals were calculated and added at a higher level to the original signal.

Robustness

The requirements for robustness were expressed as a list of processes to which an audio signal might be subject during programme production, distribution, or emission, after which it would still be desirable to be able to detect the watermark. Those used in the tests were as follows:

MPEG-1 Layer II, 128kbit/s joint stereo;
MPEG-1 Layer II, 32kbit/s mono;
Added white noise, -30dB relative to maximum level of test sequence;
pitch-corrected time stretch, 105%;
MPEG Layer III, 96 kbit/s, stereo;
MPEG Layer III, 64 kbit/s, stereo;
Linear time stretch, 110%;
Dolby AC-3, 128 kbit/s;
MPEG AAC, 32 kbit/s stereo;
voice-over, attenuation of -18.16dB;
Dynamic compression;
Minidisc;
Conversion to analogue;
Various combined processes, consistent with current broadcast chains, including BetaSP, NICAM 728, Dolby E, and so on.

To measure the robustness a series of pseudo-random payloads was embedded using each watermark system into a 20 minute selection of audio. The watermarked audio from each system was then segmented, and unrelated audio, with a fixed payload, inserted between the segments. Software to generate Cool Edit Pro session files was written to automate this task. The segmented sequences were then played into the watermark detectors. The robustness to a particular process is expressed as the number of payloads recovered as a percentage of the number of segments.

The unsegmented sequences were also played into the detectors. This makes the test less severe in some cases. The results are expressed in the same way as for the segmented signals, that is, as the number of payloads recovered as a percentage of the same number of segments.

A payload being recovered that was not embedded is called a “false positive” detection. The probability of these should be very small, so as not to cause too many false accusations of misuse. The EBU requirement was set at 10^{-8}.

Payload capacity

The purpose of applying a watermark in the EBU Eurovision distribution model is that of identification for purposes of copyright protection. The payload carried by the watermark should identify audio material uniquely, so that its use can be monitored. The shortest segment of audio that was thought to be useful, and so worth protecting, was 5s. The amount of data required to identify each segment of material was initially set at 64 bits, but this was later reduced to 48 bits.

Two different interpretations were made of the payload capacity requirement by system proponents. This meant that two series of robustness tests had to be run, one with a segment length of 5s, and another with a segment length of 10s.

Description of systems submitted for testing

Company XX supplied a PC running Linux fitted with a soundcard with S/PDIF interfaces. A simple script was run to allow the selection of embedder or one of two detector implementations (referred to as “System A” and “System B”). Payloads were read from the serial port for embedding, and written to a file on disc by the detectors.

Company YY supplied two PCs running Windows 2000 each fitted with a soundcard with AES/EBU interfaces. Programs were provided for embedding and for detecting. Payloads were read from the serial port for embedding, and written to the serial port and a log file by the detector.

Company ZZ supplied an embedder and detector, each in a 2U 19” rackmount box. The only controls on the boxes were the on-off switches. The boosted-level watermark setting was controlled by sending a special data sequence into the RS-232 port used for the payloads. Audio input and output was via AES/EBU interfaces. In preliminary tests this system was found to have some problems with false positive detections and perceptibility on some signals. As a result it was not subjected to the full set of tests.

Results of subjective tests

The results of the subjective tests are in three categories:

ITU-R BS.1116 diff-grades and 95% confidence intervals;
A Wilcoxon rank sum test on the BS.1116 diff-grades for each subjective test item;
Recognition rate from forced choice as a function of test item and of listener.

As was noted earlier, robustness tests were conducted in two phases because of different interpretations of the 5s watermark minimum segment length requirement. The formal subjective tests were conducted on the systems supplied for the first phase of robustness tests. Assurances were given by the system proponents that the alternative configurations supplied for the second phase would not differ in perceptibility. Informal, but expert, listening confirmed this.

Figures 6, 7, and 8 show results for the XX system. Figures 9, 10, and 11 show results for the YY system.

XX subjective test results

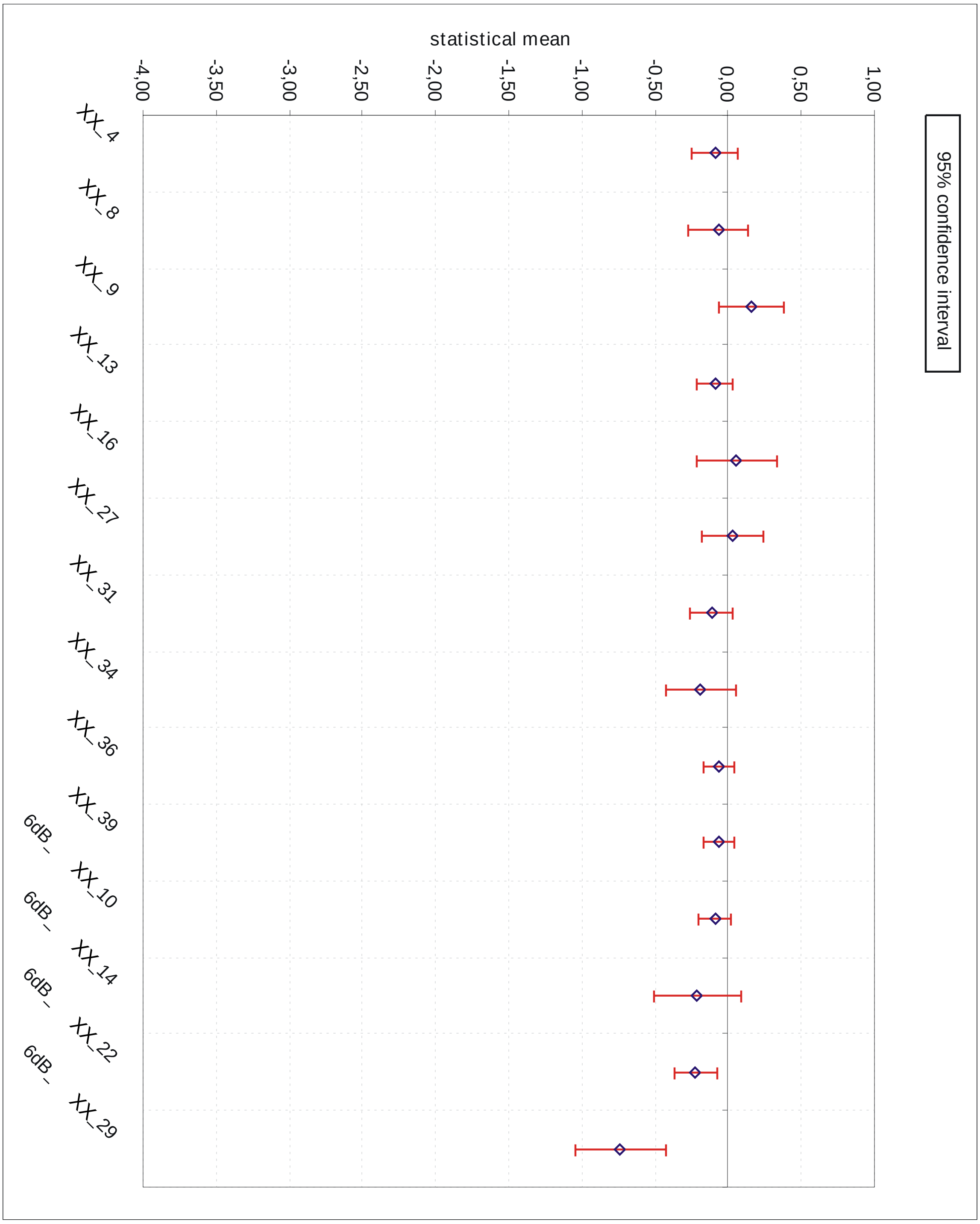

Figure 6 : Mean grade and 95% confidence interval for XX system

The Wilcoxon rank sum test on the diff-grades did not find any significant difference from the zero distribution that would be expected from un-watermarked signals.

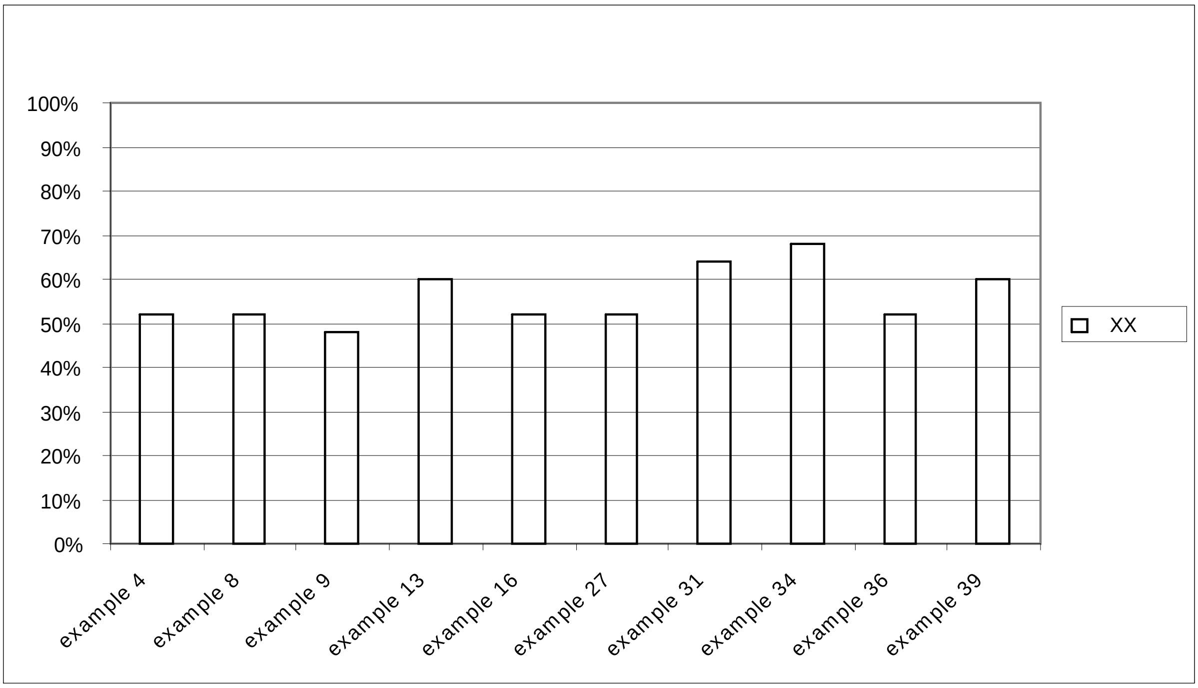

Figure 7 : Recognition rate of items for XX system

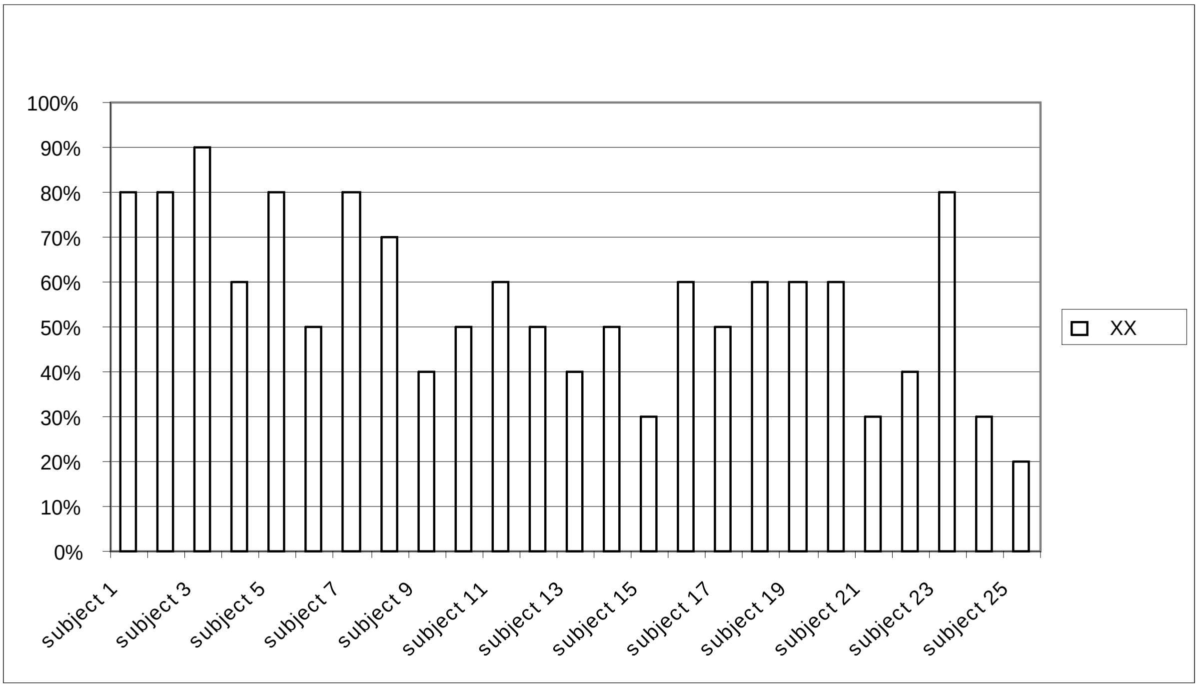

Figure 8 : Recognition rate of subjects for XX system

The overall recognition rate for the XX system was 56.0%

YY subjective test results

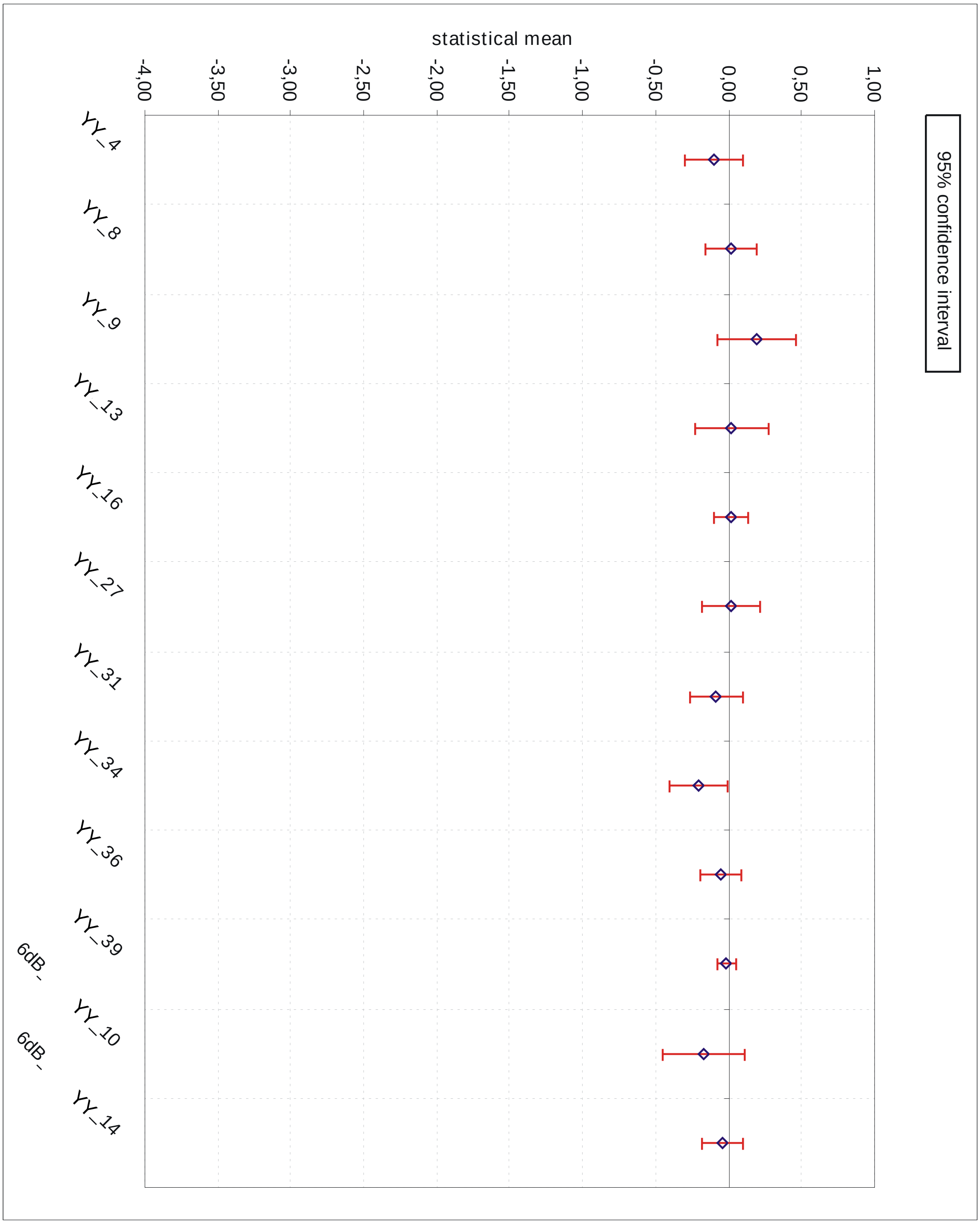

Figure 9 : Mean grade and 95% confidence interval for the YY system

The Wilcoxon rank sum test on the diff-grades showed a difference from the zero distribution that would be expected from un-watermarked signals for only one test item, number 34 (German male speech).

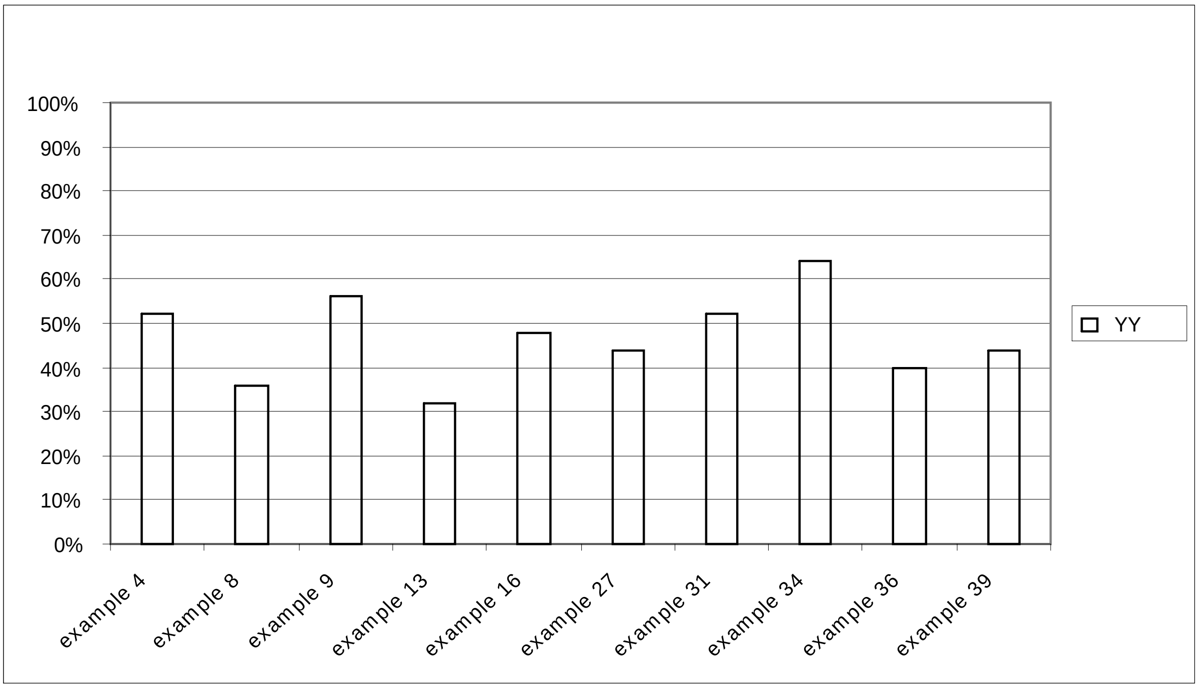

Figure 10 : Recognition rate of items for YY system

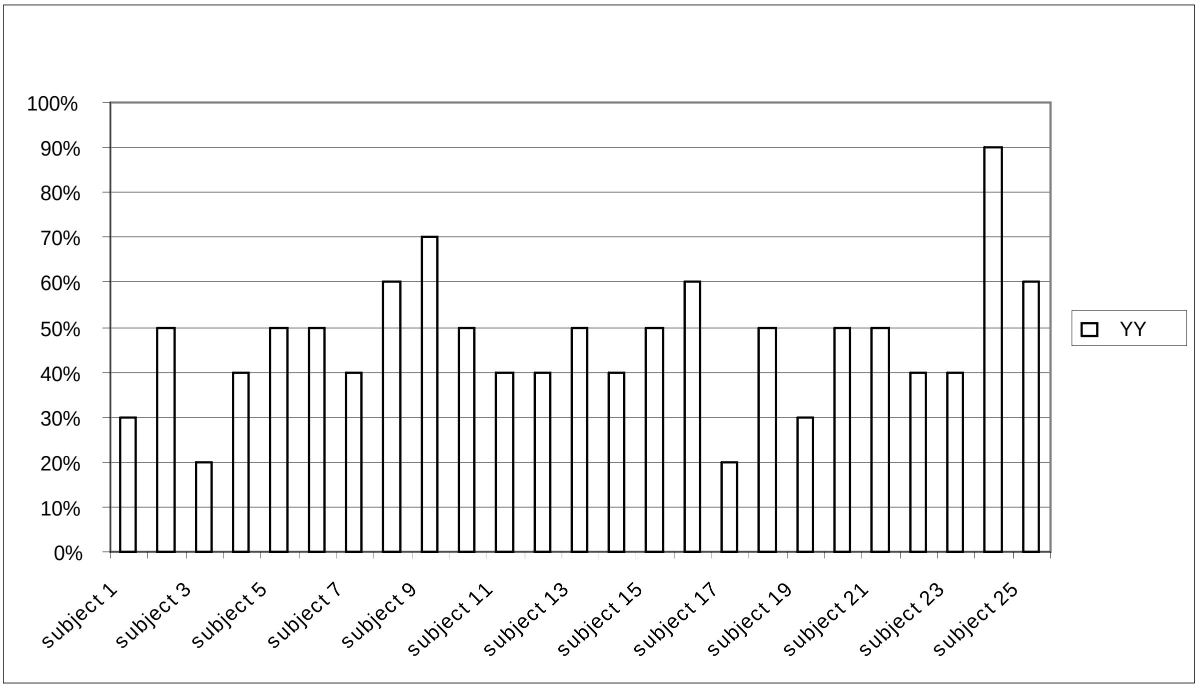

Figure 11 : Recognition rate of subjects of YY system

The overall recognition rate for the YY system was 46.8%.

Results of robustness tests

Robustness tests were run in two phases. In the first phase the XX system had an effective watermark minimum segment length of 10s and the YY system one of 5s. In the second phase the XX system was modified to have a watermark minimum segment length of 5s and the YY system one of 10s. Table 2 shows the results of the robustness tests using a 10s watermark minimum segment length (XX first phase "original" and YY second phase "bis"). Table 3 shows the results of the robustness tests using a 5s watermark minimum segment length (XX second phase "bis", and YY first phase "original").

Because of restrictions on the time available to conduct the second phase of tests not all processes were tried in the second phase: entries in the tables are left blank in this case and the rows shaded grey. Some tests caused erroneous behaviour by the detectors. In these cases it was not possible to calculate a valid result: these are shown as "-" in the tables.

Table 2: Percentage of marks recovered with 10s watermark segments:
XX system from first phase of tests, YY system "bis" from second phase of tests

	Continuous replay			Segmented replay		
Attack	XX A	XX B	YY bis	XX A 10s	XX B 10s	YY bis 10s
No attack	95.2	94.8	97.6	-	91.2	96.0
minidisc (BBC)	93.5	94.4	96.0	84.6	91.2	94.4
minidisc (TVP)	93.5	94.0		-	88.8	
Dolby AC-3, 128kbit/s, stereo	92.7	93.7		-	88.0	
MPEG Layer II, 128kbit/s, joint stereo	94.4	93.1	96.8	-	89.6	91.9
MP3, 96kbit/s, stereo	91.5	93.5	62.1	58.8	89.6	57.3
MP3, 64 kbit/s, stereo	73.8	75.0	6.5	-	63.8	8.1
AAC 32kbit/s, stereo	7.7	0.8	0.0	-	0.0	0.0
MPEG Layer II, 32 kbit/s, mono	0	0.4		-	0.0	
linear time stretch, (10%)	0	84.6	95.2	0	0.0	43.5
pitch-corrected time-stretch, 5%	0.4	0.8	0.0	1.6	0.0	0.0
voice-over, +15dB	0.8	0.0		-	0.8	
added white noise, -30dB	0.8	0.0		0.8	0.8	
dynamic range compression	95.2	95.2	96.0	60.4	92.0	94.4
analogue conversion	92.3	91.5		91.2	88.8	
combined audio processing	94.8	94.8		-	92.8	
Broadcast chain 1, FM	87.5	86.3	57.3	83.0	80.6	58.9
Broadcast chain 2, NICAM	91.5	90.3		78.2	90.4	
Broadcast chain 3, NICAM + MPEG	90.7	90.7	91.1	61.2	69.4	71.8
Broadcast chain 4, Dolby E+AC3	93.1	89.5		-	86.2	
first watermark detection after application of second watermark	95.2	94.4	93.5	-	88.8	96.8
second mark detection	94.0	95.6	96.8	-	95.2	95.2

Colour code:	100%-80%	79%-60%	59%-40%	39%-20%	19%-0%

Table 3: Percentage of marks recovered with 5s watermark segments: XX system "bis" from second phase of tests, YY system from first phase of tests

Attack	Continuous replay			Segmented replay		
	XX A bis	XX B bis	YY	XX A bis 5s	XX B bis 5s	YY 5s
No attack	98.0	98.0	73.4	- [a]	90.7	89.1
minidisc (BBC)	95.6	97.6	7.7	-	85.9	14.5
minidisc (TVP)			0.0			0.0
Dolby AC-3, 128kbit/s, stereo			0.0			0.0
MPEG Layer II, 128kbit/s, joint stereo	97.2	96.4	0.0	-	86.3	0.0
MP3, 96kbit/s, stereo	90.3	91.9	0.0	-	68.1	0.0
MP3, 64 kbit/s, stereo	56.5	42.7	0.0	-	15.3	0.0
AAC 32kbit/s, stereo	4.8	0.0	0.0	0.0	0.0	0.0
MPEG Layer II, 32 kbit/s, mono			0.0			0.0
linear time stretch, (10%)	0.0	97.2	0.4	0.0	0.0	2.6
pitch-corrected time-stretch, 5%	4.0	1.6	18.1	2.8	2.0	1.2
voice-over, +15dB			0.0			0.0
added white noise, -30dB			0.0			0.0
dynamic range compression	98.0	98.0	75.0	-	92.7	60.1
analogue conversion			0.0			0.0
combined audio processing			0.0			0.0
Broadcast chain 1, FM	79.4	63.7	0.0	32.7	52.0	0.0
Broadcast chain 2, NICAM			0.0			0.0
Broadcast chain 3, NICAM + MPEG	96.0	96.0	0.0	64.1	82.3	0.0
Broadcast chain 4, Dolby E+AC3			7.3			19.4
first watermark detection after application of second watermark	98.0	98.0	39.9	-	90.3	63.3
second mark detection	98.0	98.0	41.1	- [b]	93.5	39.5

a. When the interstitial audio was digital 0, 60.5% correct was obtained
b. When the interstitial audio was digital 0, 79.8% correct was obtained

colour code:	100%-80%	79%-60%	59%-40%	39%-20%	19%-0%

Conclusions

A call for audio watermarking systems resulted in a number of systems being submitted for test. The technical requirements listed in the call included the robustness, audibility, and payload capacity against which the systems would be evaluated. The robustness for a particular payload capacity was measured by a series of objective tests. Audibility was measured by subjective evaluation.

Subjective tests

Formal subjective listening tests were conducted, according to BS.1116 plus a forced choice, on the XX 10s watermark minimum segment length and YY 5s watermark minimum segment length systems.

Analysis of difference grades

The difference grades and 95% confidence intervals indicate that for the XX system none of the items could be said to be different from the original, while for the YY system one of the items (item 34, German male speech, EBU SQAM disc), the 95% confidence interval does not quite cross the zero diff-grade axis and so does show a difference.

The Wilcoxon rank sum test on the difference grades confirms this result: according to this test none of the items with XX watermark showed a significant difference from the original, item 34 watermarked by the YY system showed a significant difference from the original.

None of the mean difference grades for any of the items for any of the systems were lower than -0.25 and none of the 95% confidence intervals extended below a difference grade of -0.5.

Analysis of forced choice

The analysis of recognition rate merits more study. If a subject scores a high percentage of correct identifications there is a certain probability that they are able to hear the watermark rather than be guessing. However, what one should do with the cases where someone scores a very low percentage of correct identifications is not clear. Some subjects did score high recognition rates for some systems: it remains to be determined whether that was by chance or not.

Given different probabilities of audibility there are different probability distributions of recognition rate. The recognition rate required to differentiate between zero and close-to-zero probabilities of audibility has not yet been determined.

Updated systems' audibility

Informal listening to the systems updated to have a different watermark minimum segment length did not reveal any change to the audibility of the signals compared with the originally submitted systems.

Objective tests

The detectability of watermarks in response to a wide range of types of attack has been measured for systems with watermark minimum segment lengths of 5s and 10s. None of the systems proposed showed significant robustness to all of the attacks, which, it must be recognised, range from those with negligible effect on audio quality to those which produced material with questionable usability. Because of the different performance of the different systems in response to the same attack it is not possible to say that one system is always better than another.

5s watermark minimum segment length

The tests performed with a 5s watermark minimum segment showed clear differences between the systems. For unsegmented detection both XX systems showed good robustness to mild attacks, but poor robustness to some others, for example, AAC 32 kbit/s, while the YY system showed poor robustness to most attacks.

With segmented detection the XX system B detector showed quite good robustness although the detection rate fell quite rapidly for more severe attacks, for example from 68.1% to 15.3% with MPEG Layer III at 96kbit/s and at 64kbit/s respectively. XX system A was found to be unreliable with segmented signals. The YY system showed poor robustness as it did for unsegmented detection.

10s watermark minimum segment length

The tests performed with a 10s watermark minimum segment again showed some significant differences between the systems. For example, for segmented linear time-stretched material, XX had a detection rate of 0.0% while YY had a detection rate of 43.5%. On the other hand, for segmented MPEG Layer III at 64kbit/s, XX system B had a detection rate of 63.8% and YY had 8.1%. The XX system A detector was again found to be unreliable with segmented signals.

The difference between the robustness of the YY and XX systems was small for unsegmented signals with a watermark minimum segment length of 10s and mild attacks. The YY system was less robust to more severe attacks.

Overall robustness

The XX system B 10s and 5s watermark minimum segment length systems and the YY 10s watermark minimum segment length system showed reasonable robustness to attacks that did not significantly affect the quality of the audio signal. In general it was attacks that resulted in poor audio quality caused by very low bit rate coding that produced low detection rates.

The YY 5s watermark minimum segment length system was not very robust to most attacks. The XX system A detector was found not to be reliable.

The complete test report is available to EBU members[13].

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