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An Implementation of Limited Multi-Level (LML) Optical Recording

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Multi-level pits and lands are mastered compatible with the compact disc (CD) format in a sub-channel on top of the original Runlength-Limited (RLL) channel, which remains unaffected. By introducing multi-level effects only in long pit and land runlengths of the main RLL channel, two additional Limited Multi-Level (LML) channels are created. Via the restriction of the multi-level modulation to relatively long runlengths, it is realized that the jitter in the original channel is not affected and that separate (independent) slicers for all pit multi-level effects and for the land multi-level effects can be used. An additional achievement is that a slicer is devised for retrieving the LML-bits which is optimized for maintaining a maximum capacity in the multi-level channel. The LML system is evaluated using both simulations and experiments on read-only discs.

KEYWORDS: optical recording, multi-level modulation, mastering, slicer

1. Introduction

Optical recording read-out systems are based on the modulation of the reflected beam of a laser. With most optical recording techniques, binary modulation is applied with only two states being written in the medium, those being pits and lands. The photodetector delivers a high-frequency signal from which these two levels can be derived by means of a process called “slicing”. However, since the amplitude resolution of the detecting electronics can handle more levels in general, a logical topic of research is the feasibility of retrieving data from multi-level modulation in optical discs.

In history, some multi-level techniques are reported, some of them briefly summarized by Ohta *et al*.[1)] A quite straightforward method was introduced by Spielman *et al*. using pit-depth modulation, demonstrating six levels.[2)] A completely different approach, which does not need the mastering of different pit depths, is the pit-length modulation introduced by Kobayashi *et al*.[3)] Finally, the same research group published multi-level recording in the third, radial, direction by groove baseband recording,[4)] using the radial wobbling of the egdes of a continuous groove.

With all reported multi-level recording methods, there is no compatibility with existing optical recording platforms like compact disc (CD) or digital versatile disc (DVD). The advantage of the Limited Multi-Level (LML) approach introduced in this paper is that it can be placed on top of existing read-only formats. Most formats are based on runlength-limited (RLL) sequences of channel bits. The basic idea is to introduce two types of runlengths, one with maximum amplitude in the eye-pattern, the other with a reduced amplitude. For the smaller runlengths, the normal modulation is already lower than with large runlengths, due to intersymbol interference, and therefore, LML can not be applied on these shorter runlengths, hence the word “limited”.

A complete realization of LML-effects on top of a CD-ROM disc is realized. The resulting extra capacity is optimized to approximately 24%. Besides mastering the Limited Multi-Level pits and lands, attention is being paid to the read-out system. A slicer is proposed which can retrieve these bits without requiring a special DC-free LML-channel code. Therefore, no overhead is required for the channel code and the complete number of LML channel bits is available as user bits.

2. The LML Sub-channel

We consider LML recording for the CD-format. In LML-coding, multi-level modulation is reserved exclusively for the longer runlengths of an RLL encoded channel bit-stream. A 2-level modulation for pits and lands is applied, accommodating a single LML-bit for each long runlength (LML-bit = 0 for non-modified amplitude, LML-bit = 1 for a reduced absolute amplitude). The LML-channel is generated on top of the standard RLL channel, and its capacity is dependent on the occurrence of long runlengths in the RLL channel.

The minimum runlength that can be used in LML coding is determined by three conditions:

- the equalized waveform amplitude should reach the maximum level in the eye-pattern (for either the land or the pit side) in case of the non-modified runlengths. This condition is required in view of a single slicing mechanism for all LML runlengths involved;
- for the modified runlength (LML-bit = 1), the reduction in the absolute amplitude of the center part of the runlength should be large enough to create enough opening of the additional LML-eye, yet small enough in order to remain at respective distance from the standard slicer level of the main RLL channel;
- for the modified runlength (LML-bit = 1), the outer edges of the runlength in the read-out signal should not move too much away from their nominal conditions, because otherwise this would lead to an increase in jitter of the main RLL channel.

For the CD-format, the minimum runlength that satisfies the above conditions, is determined to be 5 T. This implies that each runlength equal or larger than 5 T contains a single LML-bit. The increase in capacity with respect to normal EFM can be calculated to be 24%. Note that this number is a quasi-guaranteed capacity increase, that applies for a format with LML frames of relatively large size, in view of the stochastical dependence of the LML channel capacity on the main RLL channel properties.

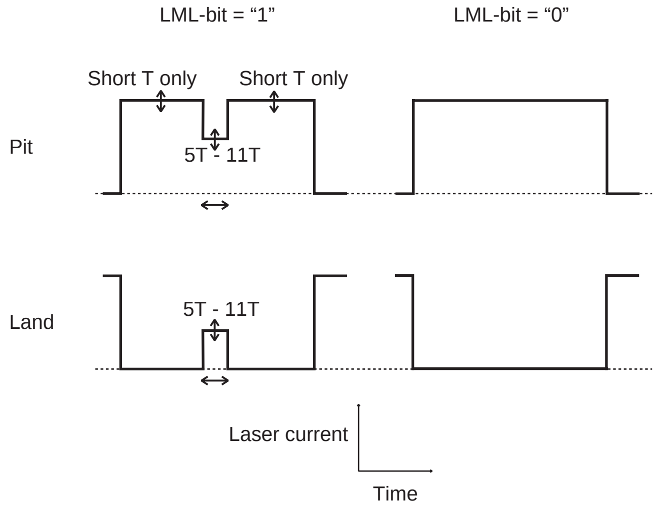

Fig. 1. Laser beam recorder current during writing reduced (left-hand) and normal (right-hand) runlengths.

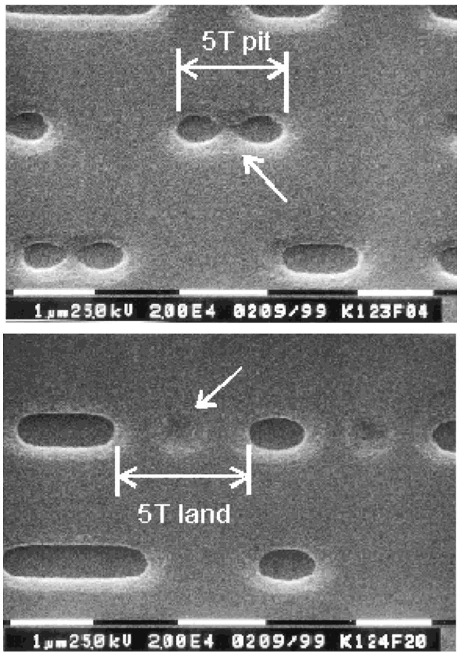

Fig. 2. SEM Pictures of a disc surface with LML-effects inserted in the 5 T pits (upper picture) and 5 T lands (lower picture).

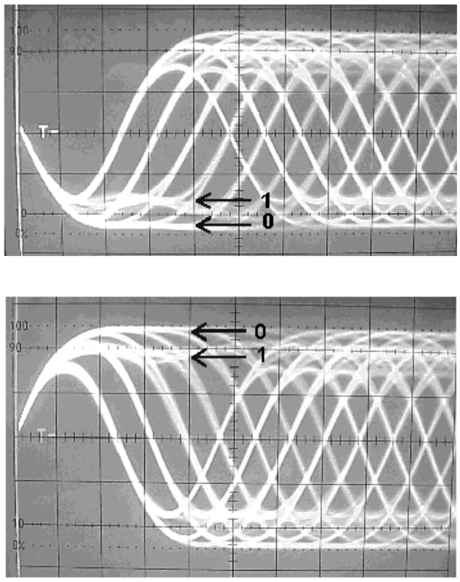

Fig. 3. Eye-patterns of an LML-modulated track.

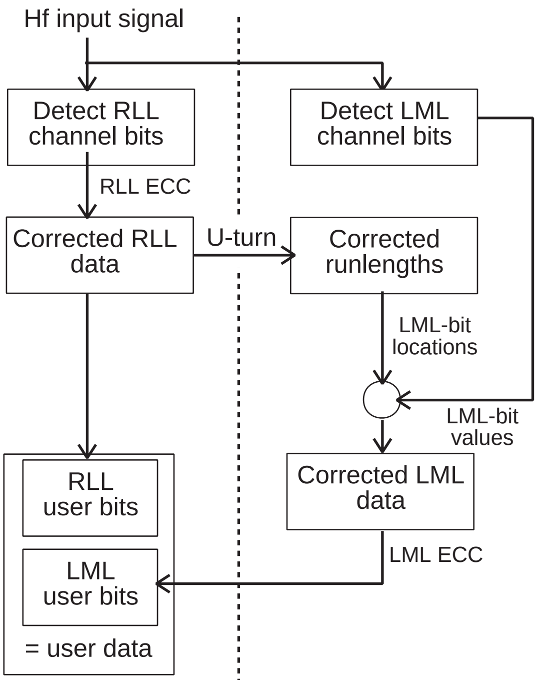

Fig. 4. General set-up of the complete RLL and LML decoding system.

3. Mastering

A number of LML discs is mastered at CD capacity without affecting the jitter in the original EFM signal. Reduced pits are created by momentarily lowering the laser beam recorder (LBR) current in the middle of a pit, reduced lands are realized by shortly switching the LBR current on in the middle of a land (Fig. 1). The widths and the current levels of these momentarily changes in the write strategy are carefully optimized for best jitter performance for each individual runlength. In addition, for the shortest LML pit-runs (5 T and 6 T), a writing compensation is applied in view of pit-length correction. Figure 2 shows a scanning electron microscope (SEM) picture of the disc surface with LML-effects in the 5 T pits and lands.

As can be seen in Fig. 3, the mastering is optimized for having a 30% reduction in the resulting equalized eye pattern. The resulting data to clock jitter measured on a CD-ROM disc with LML effects in both pits and lands of length 5 T up to 11 T is equal to 13.8 ns and 11.6 ns for the leading and trailing edge respectively (13.8 ns and 11.2 ns on the same disc on a bare EFM track as a reference).

4. LML Decoding Circuitry

In the experimental set-up, the front-end for the optical detection of information on the disc is identical to the general form used in optical recording. Figure 4 shows the complete decoding scheme for decoding the RLL sequence and the additional LML channels in the pits and the lands. The left-hand branch represents the ciruitry as is common for decoding CD channel bits into user bits. In this branch, the runlength lim-

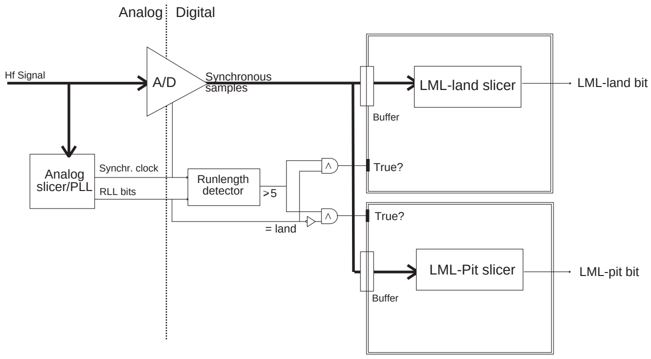

Fig. 5. Set-up of the LML evaluation circuitry.

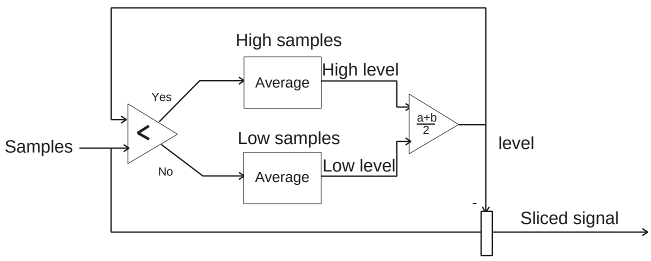

Fig. 6. The slicer which does not need a DC-free constraint.

ited sequence of pits and lands is decoded after which the error correction code (ECC) is utilized to retrieve the original user bits.

A robust retrieval of runlengths is essential in view of elimination of LML bitslips, since a runlength mistake from 4 T to 5 T will evoke an LML-bit insertion, while an erroneously detected 4 T instead of 5 T results into an LML-bit deletion error. The cross-link in Fig. 4, indicated by the word "U-turn", is used to eliminate the chance of such an insertion or deletion error.[5] Note that detection of the LML-bits occurs on the basis of the detected runlengths which may still be subject to channel errors. The U-turn is based on a re-encoding of the runlength-limited bitstream with as input the ECC-corrected data-stream. So, the LML-bit locations are derived from the standard CD main channel, while the actual values of the LML-bits are detected by the added LML decoding circuitry.

The LML-bit values are found by sampling the modulation level in the middle of an LML-runlength. This center amplitude will have the lowest distortion due to tangential tilt. Two slicers are needed to convert the modulation levels into LML-bits: one for the LML-land channel and one for the LML-pit channel.

5. A Slicer for Retrieving LML Bits

The slicer circuitry can be separated into a sample selector circuitry and two slicer instances (Fig. 5), one for the pit LML bits and one for the land LML bits. Notice that in Fig. 5 the afore mentioned "U-turn" is not explicitly represented.

The sample selector circuitry supplies the proper slicer instance with the amplitude measure of a runlength when this runlength appears to have a valid LML length (5 T or larger). Decisions on the LML-bits are made based on these amplitude measures. There is no reason to apply RLL constraints or a DC-control to the LML channel data since the clock can be derived from the EFM channel and no additional servo signals have to be retrieved. Therefore, loss of capacity can be minimized by creating a slicer which does not need a DC-free code as well.

Figure 6 shows the implementation of the used LML-slicers. Based on the previously determined slicer level, the incoming samples are qualified as "high" or "low". From the collected high and low samples, the corresponding high and low levels are determined. This can be done by either a moving average or a registered average. The middle value between the high and low level yields the new slicer level. As a consequence, both levels must occur, not necessarily with the same probability. Note that the channel code does not have to guarantee the existence of two levels in practical applications since at a higher level this condition will be met, for example by a scrambler. A scrambler is a functional block which randomizes user data in order to avoid that identical data is written to the disc over a too long period which might result into a very long sequence of a single level.

The dynamic start-up behaviour can be described as follows. Initially, both the high and low level are equal to zero and so is the slicer level. Therefore, the first samples will be qualified as being high. The result is that the high level is increasing, pulling up the slicer level as well. At a certain moment, some of the incoming samples appear to be below the slicer level with the assumption that the signal modulation is sufficiently large, as can be realised using an automatic gain control. From that moment the low level is updated and the tracking is complete.

Only in some special cases, like heavy fingerprints or erasures, the optimum slicer level might not be between the high and low levels anymore due to a sudden change in reflectivity. This situation will not be solved automatically because the system thinks the incoming samples are all high or low. In that case, indicated by one of the levels failing to appear, the start-up sequence should be re-entered again.

6. Simulations

The new approach for slicing is tested with a series of simulations using random bit sequences created with a binomial distribution. To simulate noise in the optical path, signal levels are generated using two normal distributions on top of the bit levels. In Fig. 7 a calculated modulation level distribution is placed along the vertical axis with the frequency of occurrence in the horizontal direction. In the same figure, the transient response of the slicer level on an input sequence satisfying the calculated amplitude distribution is plotted. As a reference, the response of a conventional CD slicer having a bandwidth of 3 kHz at 1X CD is visualized as well. The units on the horizontal axis are clock-cycles for the corresponding slicer, on the vertical axis the modulation level corresponding to the slicer level is shown. Obviously, the correct slicer level is found in the middle of the two incoming signal levels using either the new or a conventional slicer. Note that the bandwidth of the new slicer can be matched to the conventional situation using the amount of averaging.

However, when the ratio of high and low incoming signal levels is not equal to one, in which case the sequence can never be DC-free, the conventional slicer does not yield the

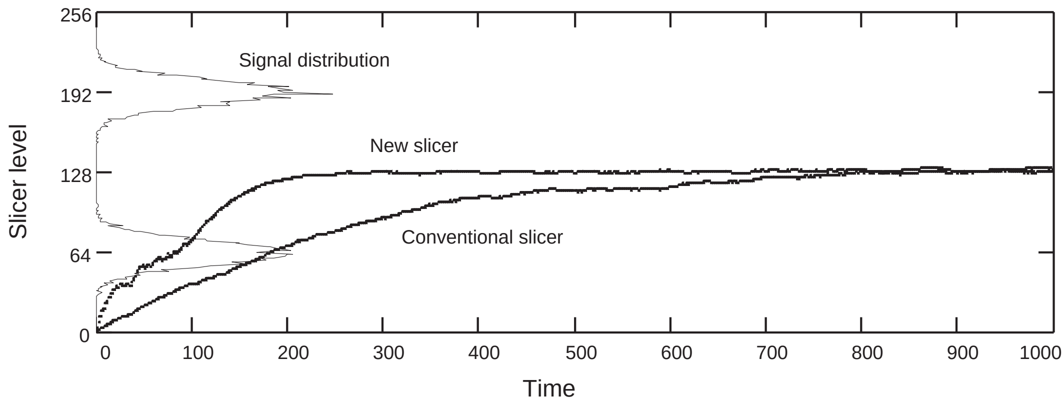

Fig. 7. Capture behavior of the new and a conventional slicer.

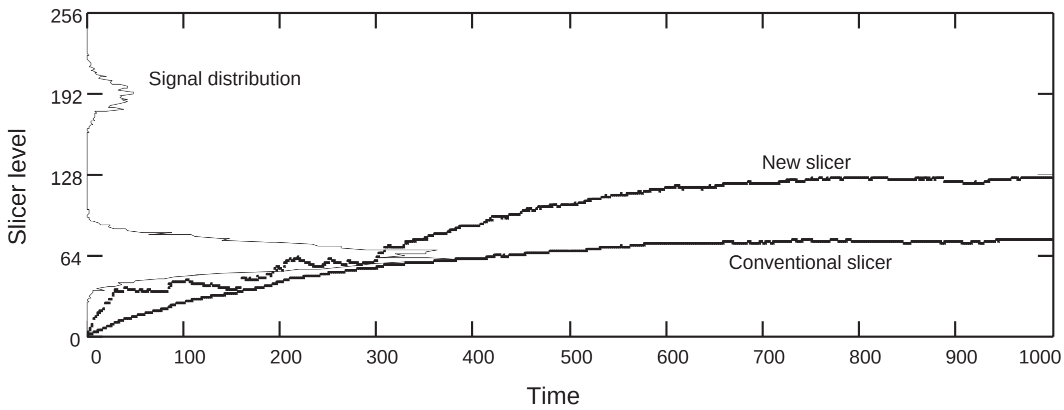

Fig. 8. Capture behavior of the new and a conventional slicer with asymmetric input signal.

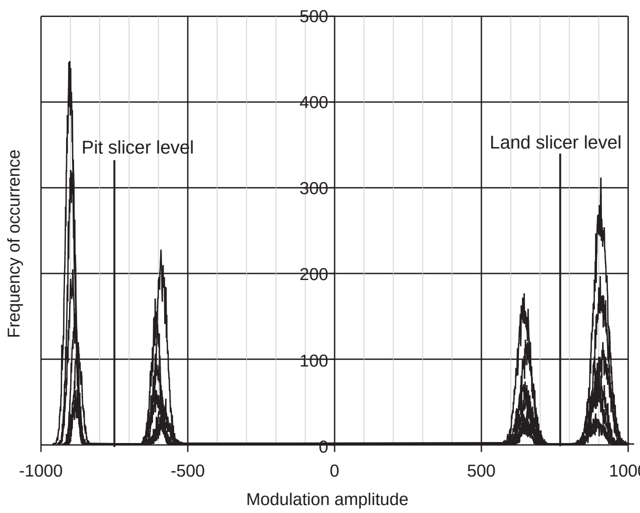

Fig. 9. Measured amplitude distribution of the hf signal.

optimum slicer level anymore (Fig. 8). As could be expected, conventional slicers which are generally based on DC-free properties do not work at all in case of such sequences. On the other hand, the new slicer is still capable of resolving the correct slicer level, however, with a decrease in response time due to the low amount of occurrences of the high level.

7. Measurements

Measurements are carried out using a CD-ROM disc with LML-effects in the 5 T up to 11 T pits and lands as described before. The measured modulation amplitude distribution for the various LML-runlengths (pit and land, reduced and normal amplitude) is shown in Fig. 9. The well-defined separation between modulation levels ensures correct slicing.

Of special interest with the measurements is the sensitivity of the slicer on the DC-level in the code. Offsets in the DC-level are created by generating LML channelbits using the binomial distribution. In the binomial distribution the chance "p" is used to define the chance that a certain individual bit will be a "1". So, this chance "p" can be used to set the ratio between the occurrence of two modulation levels within the LML channels. For example, in Fig. 10 at $p = 0.5$, the chance on a reduced modulation level (LML-bit $= 1$) is equal to the chance on a normal modulation level (LML-bit $= 0$).

The bit error rate is determined to be lower than 10^{-4} for both a conventional slicer and the new slicer. When increasing the ratio between these levels up to $p = 0.1$ (resulting in one reduced level for nine normal levels on the average), the conventional slicer is not capable of returning the correct bits. On the other hand, the new slicer with the principle of Fig. 6, is not affected by the increase in DC content in the code.

We have analyzed the performance of the LML-bit detection for radial tilt. When radial tilt is increased, the bit error rate (after the previously mentioned U-turn runlength correction) is shown in Fig. 11. Up to a radial tilt angle of 0.5° the

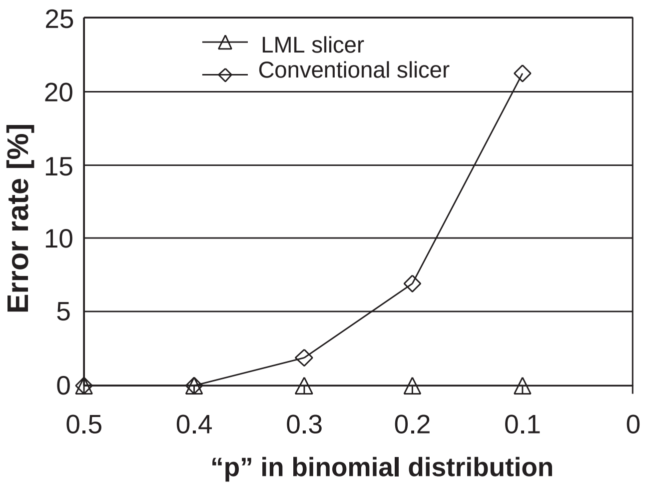

Fig. 10. Measured error rate as a function of the ratio between high and low levels.

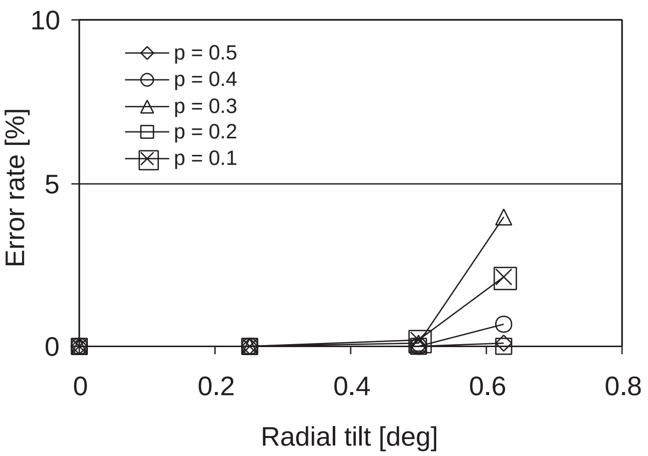

Fig. 11. Measured dependence on radial tilt.

LML bit retrieval is still satisfying.

Tangential tilt manifests as skew shaping in the hf-signal: the modulation at the beginning and end of a runlength is dependent on tangential tilt, while the middle is unaffected. Therefore, distortion due to tangential tilt is minimized by sampling the LML-bits in the middle of runlengths. However, this is not measured explicitely.

8. Conclusions

A complete system for mastering and retrieving a limited multi-level channel is developed based on the CD-ROM standard. A capacity increase of 24% can be obtained. Special attention is being paid to slicing the LML-pit and LML-land channels without the requirement of applying a DC-free coding technique.

Limited Multi-Level coding has the advantage that it can be placed on top of existing read only formats. The original runlength limited sequence is maintained and can still be read out using a conventional player. The additional LML-channel decoding circuitry can simply be added to the front-end of the player since the optical path is not modified. So, compatibility towards optical recording systems as placed in the market is the main advantage of LML-recording.

Normally, with optical recording, the bit-detection is closely related to timing recovery. This is not the case with LML since it is an add-on channel. Timing recovery is already carried out by the RLL channel decoder. A direct result is that a special channel coding can be omitted in the LML-channels. The presented slicer is optimized for retrieving bits from random bitstreams. Measurements showed that even bit sequences with DC-components can be decoded correctly which is not possible using conventional slicers.

Application of LML for other formats, like DVD, is still a topic of reasearch. It is expected that the capacity gain obtained with LML will be relatively lower because of the tighten system margins compared to CD, assuming that the same detection strategy as denoted in our paper is being applied.

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