Signal Processing and Coding for M-ary Optical Storage

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***Abstract*— In this paper we introduce the theoretical and practical concepts behind *M*-ary signaling on optical recording systems such as compact disc (CD), digital versatile disc (DVD) and evolving next generation blue laser formats. We show that there is sufficient signal-to-noise ratio on all recording formats (ROM, R and R/W) and give examples of how density and data transfer rate can be improved by two to three times with no changes in disc media or recorder.**

I. INTRODUCTION

Conventional optical recording systems use binary signaling for ROM, recordable (R) and rewritable (RW) formats. The signal-to-noise ratio of conventional media is typically 20-26 dB which is sufficient SNR to support *M*-ary signaling,. Commercially available systems based on binary saturation recording fail to use that SNR efficiently. In this paper we show some fundamental (information theoretic) limits associated with R, RW, and ROM media and describe how *M*-ary methods achieve between 80-90% of the theoretical limits. We shall also discuss some implementation details of an ASIC chip that has been developed and implemented (by Calimerics, Inc.) on CD, DVD and Blu-ray platforms to achieve 2-3x increase in storage capacity on off the shelf ROM, R, and RW media using pulse amplitude modulation with *M*=8 and *M*=12. Much of the gains come from coding and signal processing using tools that have been well-known in communications industry for more than thirty years.

II. BACKGROUND

The idea of multi-level amplitude modulation (AM) has been documented in optical data storage circles since at least the early 1980's. Any attempt to produce a commercially viable *M*-ary system must use the available infrastructure as much as possible, resulting in few, if any, changes to the optical, mechanical, and media components of the optical drive. Figure 1 shows the essential differences between binary and *M*-ary signaling on a conventional media like CD-R. In Figure 1a the pit (mark) profiles, reflected optical signal and optical detector signals are shown. In conventional binary CD and DVD, information is encoded the lengths of pits and the spacing between them. In Figure 1b careful control of the recorded pits and relative spacing between them can result in the ability to index any desired level of reflected light. As can be seen in Figure 1b the many different kinds of stored marks can be used to produce 'gray' levels of light from the disc. In the system of Figure 1b information is encoded in the amplitude of the reflected light at T second intervals; no information is encoded in length. The key is reliably indexing *M* signal levels in a simple, cost effective manner. This is not addressed here, it has been discussed at length in [1-3]. Briefly it requires relatively simple, nonlinear *precompensation* that can be implemented in a lookup table. The *M* levels are written in triplets to compensate for several nonlinear effects.

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Figure 2 shows the 'eye diagram' of the raw analog read from the disc that uses *M*=8 levels and nonlinear precompensation. As was indicated, information is encoded in amplitude only and the length of the recorded marks is not modulated. In the absence of intersymbol interference this results in one of *M*-levels being indexed every T seconds and this is demonstrated in Figure 2. Figure 3 shows histograms of the *M*=8 levels and their variations (indicating the random noise component). The results in Figures 2 and 3 are very typical of CD, DVD and Blu-ray systems that use R, RW, and ROM media. Next we show that conventional systems have sufficient SNR to support this *M*-ary signaling.

III. SIGNAL-TO-NOISE RATIO, FUNDAMENTAL LIMITS, AND PRACTICAL CONSDIERATIONS

To avoid confusion we have defined an SNR measure based on the ratio of noise standard deviation σ - to - dynamic range (SDR) of the recorded signal. Typical SDRs for *M*-ary signaling on conventional media are in the 2-3% range, and of course this is closely related to the peak signal-to-noise ratio, and the usual (RMS) SNR is easy to derive from that. As an estimate of the fundamental limits we shall use $C = 0.5\log_2(1 + SNR)$, which is the well-known capacity of an AWGN channel with an average power constraint. We also consider the mutual information between channel inputs and outputs assuming *M* levels with equally likely, equally spaced inputs. Figure 4 shows the capacity and mutual information as a function of SDR for $M=8,10,12,\infty$. It is easy to see that an optical disc has sufficient SNR to store about 3 bits/symbol – about double that of standard binary methods that use runlength limited coding. One interesting observation is that the AWGN model assumption is actually quite accurate from a design perspective – our experience is that designing to an AWGN model is good to first order, namely actual data matches quite well with the AWGN model assumption for both M=8 and M=12 systems.

Table 1 shows the key parameters of binary and *M*-ary system for CD, DVD and Blu-ray for *M*=8 and *M*=12. This table shows that in general there is sufficient SNR to use both *M*-ary signaling and to reduce the size of the minimum size marks o the disc. For example in the CD system, conventional binary recording uses 833nm marks with a code that achieves 1.41 bits/mark. In the *M*=8 implementation for CD the size of the mark is 600nm and the coding density is 2.5 bits/600nm mark resulting in a 2.5x improvement in storage density.

Figure 5 shows a system block diagram that gives the coding and signal processing aspects of the system that have been designed and implemented in the Calimetrics ASIC. The coding design is a concatenated code that uses an outer product Reed Solomon code and an inner *M*-ary modulation code (trellis code or turbo-like code). The outer code is used to handle large burst error cause by scratches and media defects. The inner code is predominantly for coding gain and is not used to any great extent for handling the burst errors. The outer RS code is very similar to the RS product used in conventional DVD – a product (182,172,5) x (208,192,8) RS code over GF(256). This code is capable of correcting 8 row-errors which translates to a burst of (8*182*8) = 11648 bits. The row RS code is mostly used for error detection, and for a huge majority of the cases the length of the correctible burst is double that given above. This translates to a scratch of about 1mm.

The modulation code used depends on the number of levels and desired density. The first of these codes increase the density to up to 2.8 bits/data-cell for both CD and DVD systems. To go to higher densities, it is necessary to use more levels (even with no noise, the maximum possible density using 8 levels is 3.0 bits/data-cell). With 12 levels, our second code achieves 3.08 bits/data cell with excellent bit and sector error rates on commercially available DVD media. The methods employed for each of these components as well as other key parameters of each system are shown in Table 1. The optical parameters are identical to conventional DVD (re)writable. In what follows, we give more details of these ML™ coding methods.

Code 1: 8-level, 2.8 bits/data-cell. Figure 7 shows 8 levels and a particular 3-bit labeling for each of the 8 levels. According to the labeling, one notices that in the presence of level noise, the most significant bit (MSB) is easier to recover than the other bits. This is because the MSB of levels 1-4 are all zero, while the MSB for the levels 5-8 are one. A similar arrangement exists for the second MSB, while the LSB is the most difficult bit to reliably recover. A good code design matches the reliability of the bits to the power of the code. Therefore, we more heavily code the unreliable LSB and leave the two other bits uncoded. Figure 8 shows this multi-stage encoding structure. The density in bits/data-cell can be computed as follows: The LSB conveys ~4/5 of a bit/data-cell and the other bits convey 1 bits/data-cell, thus the total amount of information per symbol is (1+1+4/5) = 2.8 bits/data-cell. The 4/5 code is a product code where the row and column codes are single error correcting (extended) Hamming codes. The data array encodes 57*57 bits into 64*64 coded bits for a rate of R=(57*57)/(64*64) = 0.79 (~4/5).

Code 2: 12-level, 3.08 bits/data-cell. Figure 8 shows how a pair of 12 level data-cells is mapped to 7 bits. The 2-dimensional, 144-point constellation is segmented into 8 sub-constellations of 16 points. Only 128 of the 144 points are used; so it takes 7 bits to select a point in the constellation of points. The 3 LSBs (of the 7 bits) are used to select one of the 8 outer sub-constellations, and the remaining 4 MSBs are used to select a point within a sub-constellation. The 3 LSBs are Gray coded, while the 4 MSBs come from a rate 0.79 extended Hamming code. The total density for the M=12 system is 3+(.79)*4 = 6.16 bits/2-data-cells = 3.08 bits/data-cell.

Equalization. Read signal ISI is dealt with by using a simple zero-forcing adaptive equalizer to allow for media and drive-to-drive variations on a sector-by-sector basis. It turns out the zero-forcing equalizer is nearly optimum since the noise power spectral density is shaped almost entirely like the channel, so the inverting filter is also the whitened-matched filter.

Performance. Figure 4 shows the density vs. SDR for numerous codes on CD-RW and DVD-RW discs at a raw (uncorrected) BER of 1e-5. After the outer ECC, all errors are fully correctable. The plot shows good SDR performance for both 8 and 12 DVD systems. The capacity limit (smooth curves) is calculated using the standard Shannon capacity for a multilevel Gaussian channel. This indicates that while there is some room for improvement, we are achieving excellent results (>90% of capacity for the 3.08 code) and that further improvements may come at the expense of higher complexity.

REFERENCES

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[2] S. McLaughlin, *et al*, "Advanced coding and signal processing for multilevel recordable and write-once optical data storage," ODS 2001, Santa Fe, NM , May 2001.

[3] K. Balasubramanian, *et al., "*Rewritable multilevel recording using blue laser and growth-dominant phase-change optical discs",ODS 2001 22-25 April 2001 Santa Fe, NM.

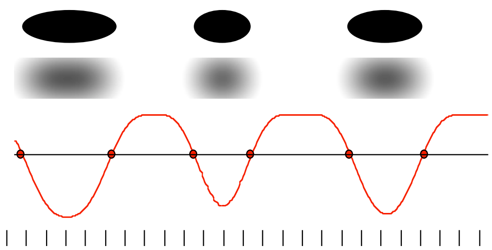

Figure 1a: Binary signaling

Top: physical marks stored on the disc, **Middle:** optical intensity reflected from disc, **Bottom:** analog signal produced by detector. Marks are modulated according to 'runlength-limited' coding and information is recorded in length of marks and spaces between them.

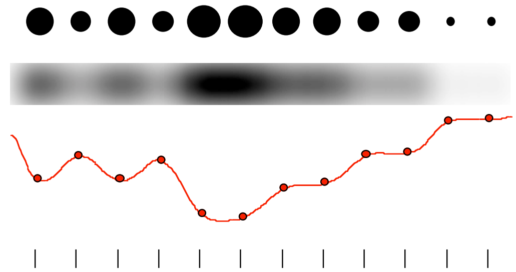

Figure 1b: *M*-ary signaling for 'R' media

Top: physical marks stored on the disc, **Middle:** optical intensity reflected from disc, **Bottom:** analog signal produced by detector. Marks are modulated every T seconds – intensity of read-back signal is determined by size and relative positioning of marks.

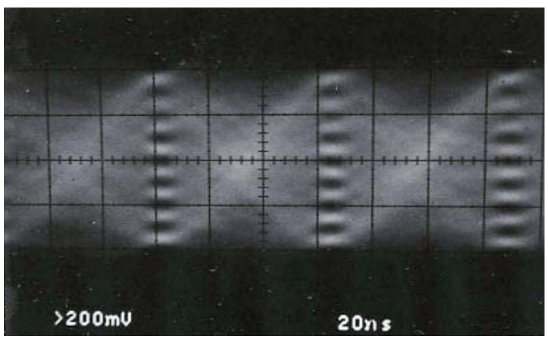

Figure 2: Eye diagram of 8-PAM on CD-RW after low pass filtering. Signal is sampled every T seconds, *M*=8 levels are clearly distinguishable at sample instants.

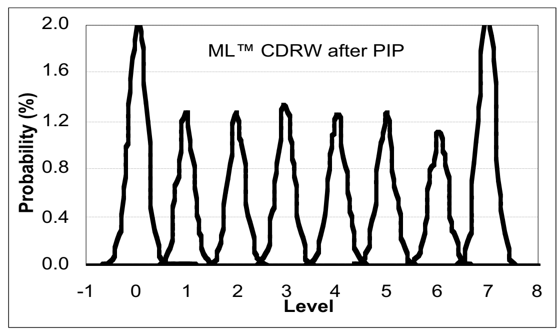

Figure 3: M=8 signal levels and noise histograms

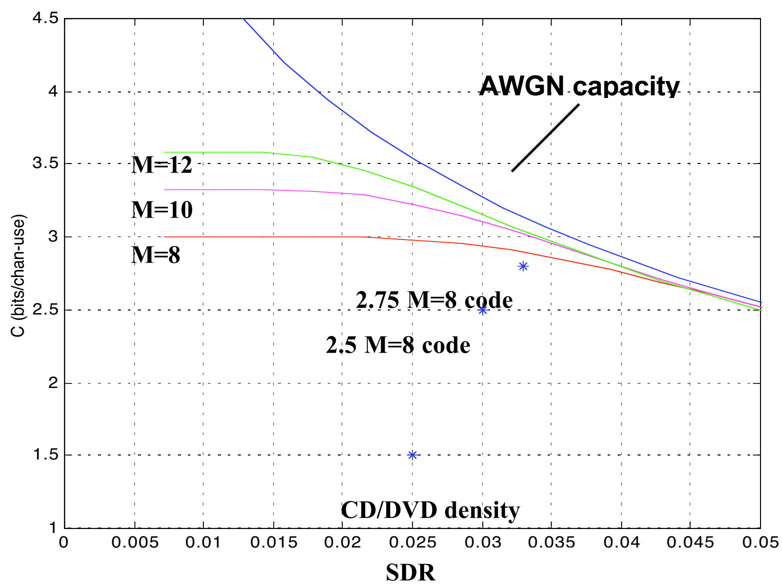

Figure 4: AWGN capacity and mutual information for M=8, 10, 12 levels. This Figure shows that for typical sigma-to-dynamic (SDR) the theoretical storage capacity is 3.0-3.5 bits/symbol – nearly double that achieved by conventional recording systems. The 'AWGN capacity' curve is the ultimate limit assuming infinite signal levels.

	M=2		M=8		M=12	
	Tmin	Coding density (bits/Tmin)	Tmin	Coding density (bits/Tmin)	Tmin	Coding density (bits/Tmin)
CD-R,RW, ROM	0.833mm	1.41	0.600mm	2.5	0.600mm	3.10
DVD-R,RW,ROM	0.400mm	1.50	0.398mm	2.5	0.398mm	3.10
Blu-ray	0.160mm	1.33	0.175mm	2.5	0.185mm	3.10

Table 1: Comparison of binary and *M*-ary systems. Tmin is the size of the smallest stored mark for the given system.

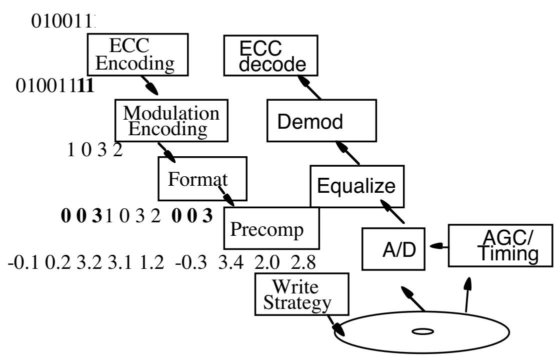

Figure 5: System components

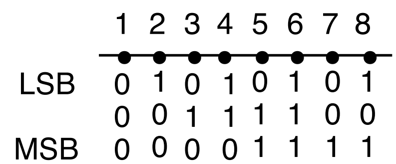

Figure 6: M=8 levels and bit label

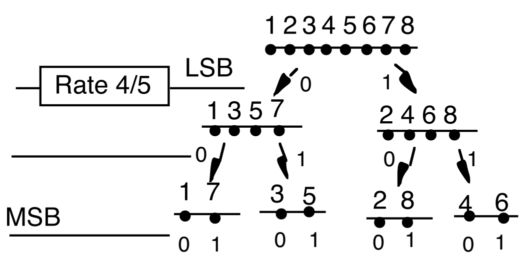

Figure 7: Encoder for 2.8 bits/data-cell

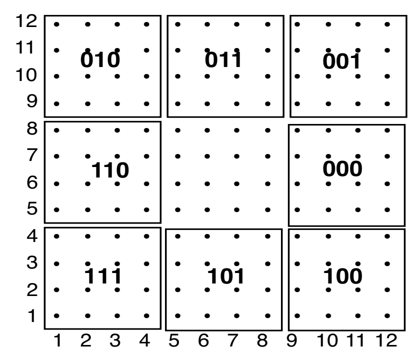

Figure 8: Two-dimensional, M=12 constellation for density 3.08 code

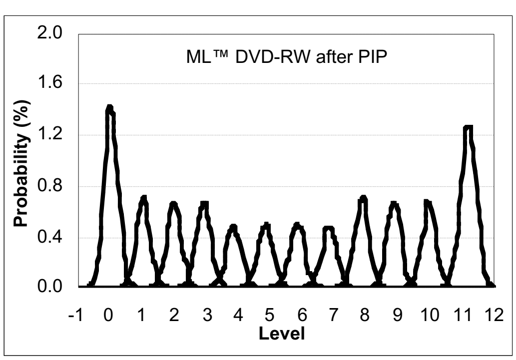

Figure 9: M=12 levels on DVD

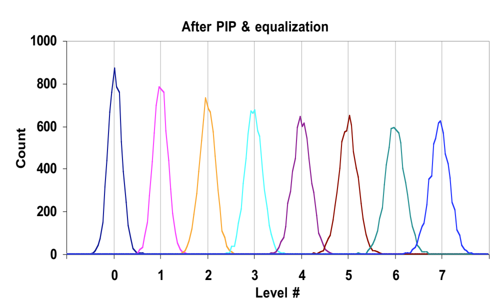

Figure 10: M=8 levels on Blu-ray