On the Value of Two-Dimensional Fixed-Length Modulation Codes for Digital Data Storage on Microfilm

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Abstract

Microfilm-based long-term data storage is an emerging technology in the archiving sector. Its estimated lifetime of up to 500 years outperforms other storage media like CDs, DVDs, hard drives, or magnetic tapes and makes this technology especially suited for archiving of digital data. Previous work has shown that the grid space, i.e., the distance between the exposure points, is a crucial parameter for the storage capacity. This paper presents investigations on a set of fixed-length modulation codes that can be employed to decrease the grid space at the expense of additional redundancy. The main question we address is, whether the smaller grid spaces achieved through such a modulation code justify the additional redundancy with respect to the overall storage capacity. Therefore, simulations based on realistic system parameters are carried out. Surprisingly, it turns out that the use of the analyzed modulation codes is questionable or even not advisable for digital data storage on microfilm.

1. Introduction

For storing digital data, common storage media are, e.g., CD, DVD, Blu-ray, magnetic tape, or hard drives. Regarding long-term storage, these media suffer the problem of a comparatively limited lifetime. Another problem is the availability of corresponding reading devices after a while. Currently, long-term storage solutions usually require migration, i.e., the data has to be copied to a different storage medium or even storage system in certain time intervals [1]. One major disadvantage of these solutions are the time-consuming and costly migration steps.

The medium *microfilm* has been used in long-term storage for quite some time already to store images and documents as analog photographs. One major advantage of microfilm is the estimated storage lifetime of up to 500 years, depending on the film material and the specific storage conditions [2]. To extend its advantages to digital data, microfilm has been suggested as a long-term storage medium for digital information [3, 4]. Particularly for digital data, microfilm offers several further outstanding advantages. For instance, it is forgery-proof and also the actual condition of the medium can be inspected by visual means (not possible for media as, e.g., magnetic tape). Furthermore, it allows the storage of analog images and digital data on the same medium and reading devices are technologically simple to construct. The fundamental idea to store digital information on film is not new, see for example [5]. Meanwhile, advances in laser exposure technology [6–8] have enabled entirely new possibilities to this field of technology. Recently, first research results for this upcoming technology have been presented [9–11].

It became clear that the grid space d, i.e., the distance between exposure points, is an important parameter towards increased storage capacities [9]. Therefore, it should be chosen as small as possible. However, smaller grid spaces increase the intersymbol interference (ISI) between adjacent exposure points and thereby limit the minimum possible grid space d. Of course, the amount of ISI can be reduced by scaling down the size of the exposure points. This, however, requires hardware changes, it is costly, and only possible within certain physical limitations.

A promising approach towards an increased storage capacity without hardware changes are modulation codes [12–16]. A modulation code can enable the use of a smaller grid space d by introducing additional redundancy to the data according to a code rate r_m. Clearly, for the overall storage capacity, there exists a tradeoff between code rate r_m and grid space d.

In [12, 13] a set of two-dimensional fixed-length modulation codes has been suggested for optical data storage systems. In our paper we investigate the value of these codes for digital data storage on microfilm. A number of simulations based on realistic system parameters are carried out to analyze the usefulness of these codes for the regarded application.

This paper is organized as follows: The next section provides an introduction to digital data storage on microfilm, including a detailed discussion on possible storage capacities and important system parameters. Section 3 gives a brief introduction to the employed modulation codes followed by the description of the simulation structure and the simulation results (Section 4). The results from these simulations will be analyzed with respect to storage capacities. Finally, conclusions and suggestions for further development will be stated.

2. Digital Data Storage on Microfilm

Regarding data storage on microfilm, the digital information is stored within so-called exposure points. These exposure points are written to the film by means of a laser recorder. As an example, Figure 1 shows a microscopical image of such exposure points.

2.1 Laser Recording

In principle, a laser recorder is based on a modulated laser beam that is moved over the film stripe, thereby writing a data pattern or alternatively an analog image onto the microfilm. As usual in photography, the film is developed and fixed afterwards in order to make the data pattern (or image) visible and to stabilize it [17]. Depending on the recording system, it may also be possible to use amplitude modulation. Moreover, color laser film recording is feasible by using three separately modulated lasers with the colors red, green, and blue. Laser film recorders are well-established to expose digitally produced 35 mm cinema film [6, 18, 19]. Recently, this technology became also available for microfilm [7, 8].

For the experiments described within this paper, the Arche laser recorder (formerly Archive-Laser®) has been utilized [7]. It is de-

Figure 1. Microscopical image of exposure points ($P = 2$ amplitude levels, $d = 9\,\mu\mathrm{m}$ grid space).

signed to expose imperforated 35 mm color or black-and-white microfilm using frames of size $32\,\mathrm{mm} \times 45\,\mathrm{mm}$ with a spatial resolution of 10666×15000 exposure points if a $d = 3\,\mu\mathrm{m}$ grid space is used. All experiments in this paper are based on negative black-and-white microfilm.

2.2 Storage Capacity

The storage capacity of a microfilm-based data storage system is mainly dependent on at least three parameters: the grid space d, the number of amplitude levels P, and also the code rate r of a forward error correction code [9, 20]. The grid space d represents the spacing between the exposure points and the code rate r is defined as the number of data (net) bits K divided by the number of total (gross) bits L including the redundancy:

$$r = \frac{K}{L}, \quad 0 < r \leq 1 \quad . \tag{1}$$

Accordingly, the storage capacity C is inversely quadratically dependent on the grid space d

$$C \propto \left(\frac{1}{d}\right)^2 \tag{2}$$

and linearly dependent on the code rate r:

$$C \propto r \quad . \tag{3}$$

For the number of amplitude levels P, this dependency is only logarithmic:

$$C \propto \log_2(P) \quad . \tag{4}$$

Possible absolute values for the storage capacity depending on these three parameters are further discussed in [9].

When applying *modulation* coding to data storage on microfilm, a fourth factor has a major influence on the storage capacity: the code rate of the modulation code r_m. A modulation code can reduce the ISI and thus allow smaller grid spaces d. Its influence on the storage capacity is linear:

$$C \propto r_m \quad . \tag{5}$$

It becomes clear that all these parameters interact and must be jointly optimized to achieve an optimum storage capacity:

$$C \propto \log_2(P) \cdot \left(\frac{1}{d}\right)^2 \cdot r_m \cdot r \quad . \tag{6}$$

2.3 Modelling Exposure Points

Various experiments have been carried out to analyze important system parameters (cf. [9]). Therefore, a series of test patterns has been inspected by means of a high-quality research microscope with a high resolution camera. All these measurements are based on the Arche laser recorder [7] and black-and-white microfilm. It turned out from these investigations that the intensity profile of the exposure points can be well-approximated by a 2-D Gaussian-shaped function

$$f(x, y, A, \mu_x, \mu_y, \sigma_x, \sigma_y) = A \cdot \exp\left\{ -\frac{1}{2}\left[\left(\frac{x-\mu_x}{\sigma_x}\right)^2 + \left(\frac{y-\mu_y}{\sigma_y}\right)^2 \right] \right\} \tag{7}$$

with the continuous coordinates x, y and the amplitude value A. The variables μ_x, μ_y define the center and the parameters σ_x, σ_y the shape of an exposure point's intensity profile. A nonlinear least squares fit analysis has shown a rotationally symmetric intensity profile with $\sigma_x = \sigma_y = 2.21\,\mu\mathrm{m}$ (see [9]). The amplitude value A is normalized to take on values within the range $A \in [0, 1]$.

3. Two-Dimensional Modulation Coding

Basically, the aim of modulation coding is to avoid data patterns which lead to strong ISI. For digital data storage on microfilm, it is desirable to decrease the amount of ISI by reducing the maximum number of exposure points in the neighborhood of non-exposed grid points.

3.1 Fixed-Length Modulation Codes

A couple of modulation codes for page-oriented optical data storage have been suggested by Pansatiankul and Sawchuk [12, 13]. Due to the similarities to data storage on microfilm it is straightforward to apply these codes to this storage technology. The ISI is caused by the low pass character of the transmission channel. Therefore, it is reasonable to distribute the information to lower frequency components. This avoids disturbances due to the formerly mentioned low pass character. A simple coding scheme that can be applied is a repetition code, where a logical one (for reasons of simplicity referred to simply as *one* in the following) is coded into a block of $N \times N$ ones and a logical zero (referred to as *zero* in the following) is coded into $N \times N$ zeros. Unfortunately, the resulting code rate is only $r_m = 1/N^2$.

Following [12, 13], a family of modulation codes can be described by

$$(M, N; L; \alpha, \beta)$$

where L denotes the number of input bits that are mapped to a code block of size $M \times N$. At the same time, the conditions that a zero has at most α ones in its four element neighborhood and at most β ones in its additional eight element neighborhood have to be fulfilled. These conditions have to be met for the $M \times N$ codeblock itself as well as for each other $M \times N$ block. The four element neighborhood describes the four direct vertical and horizontal neighbors, whereas the eight element neighborhood additionally includes the four diagonal neighbors. The code rate of such a modulation code is given by

$$r_m = \frac{L}{N \cdot M} \quad . \tag{8}$$

In the following, three different two-dimensional modulation codes as described in [12, 13] are further regarded:

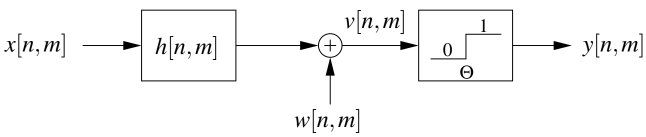

Figure 2. *The simulation structure in analogy to [12, 13].*

The $(3,3;4;2,3)$ modulation code assigns four bits a_0, a_1, a_2, a_3 to a 3×3 block according to

$$\begin{bmatrix} a_0 & a_1 & a_2 & a_3 \end{bmatrix} \longrightarrow \begin{bmatrix} 0 & a_1 & 0 \\ a_0 & X & a_3 \\ 0 & a_2 & 0 \end{bmatrix},$$

the bit X in the middle being chosen to one if more than 50% ones are contained in a_0, a_1, a_2, a_3. Otherwise it is chosen to zero. The code rate of this code is $r_m = 4/9$. Regarding the value of r_m, it has to be considered that the bit X can also serve for error detection purposes.

The $(3,3;6;3,2)$ code assigns six bits $a_0, a_1, a_2, a_3, a_4, a_5$ to a 3×3 block according to

$$\begin{bmatrix} a_0 & a_1 & a_2 & a_3 & a_4 & a_5 \end{bmatrix} \longrightarrow \begin{bmatrix} a_0 & 0 & a_3 \\ a_1 & 0 & a_4 \\ a_2 & 0 & a_5 \end{bmatrix},$$

satisfying the condition that a zero has at most three ones in its four element neighborhood and at most two ones in the additional diagonal neighborhood. Accordingly, it can be identified as a modulation code with rate $r_m = 2/3$.

For the $(4,4;8;2,2)$ code, a code block of size 4×4 is used. Eight bits $a_0, \ldots, a_7$ are assigned to the matrix

$$\begin{bmatrix} a_0 & a_1 & a_2 & a_3 & a_4 & a_5 & a_6 & a_7 \end{bmatrix} \longrightarrow \begin{bmatrix} a_0 & a_1 & 0 & 0 \\ a_2 & a_3 & 0 & 0 \\ 0 & 0 & a_4 & a_5 \\ 0 & 0 & a_6 & a_7 \end{bmatrix},$$

the code rate being $r_m = 1/2$. The code ensures that a zero has at most two ones in its four element neighborhood as well as in the four additional bits of the eight element neighborhood.

4. Simulations

In order to evaluate the performance of the described codes for digital data storage on microfilm, a set of simulations was carried out. For this simulations, rotationally symmetric exposure points were assumed with $\sigma_x = \sigma_y = \sigma$. The value $\sigma = 2.21\,\mu$m was obtained from measurements (cf. [9] and Section 2.3).

4.1 Simulation Setup

Basically, the simulation is based on the transmission model suggested in [12, 13] (see Figure 2) whereby the channel is assumed to be linear (see also [10]). The modulation coded data $x[n,m]$ is convolved with the discrete estimated point spread function $h[n,m]$ of the storage system. After adding Gaussian white noise $w[n,m]$ with standard deviation σ_n, we get:

$$v[n,m] = x[n,m] * h[n,m] + w[n,m]\,. \tag{9}$$

A hard decision demodulator with threshold Θ is used for obtaining the binary output $y[n,m]$ from the channel output $v[n,m]$:

$$y[n,m] = \begin{cases} 1 & \text{for } v[n,m] \geq \Theta \\ 0 & \text{for } v[n,m] < \Theta \end{cases}\,. \tag{10}$$

After decoding $y[n,m]$, the bit error rate p_e can be calculated by comparing the demodulated data with the original data.

The discrete point spread function $h[n,m]$ was obtained by integrating the intensity profile given in (7) over the grid space areas of the size $(d \times d)$ and truncating the result in such a way that at least 90 percent of the ISI is taken into account. For all the investigated grid spaces $d = \{3,4,5,6\}\,\mu$m a point spread function with the dimensions of 3×3 was sufficient.

For the simulations, a constant dynamic range for the coded and the uncoded case has been assumed. However, the maximum possible amplitude level is dependent on α and β. Therefore, the point spread function has been multiplied by a constant factor to achieve an identical maximum amplitude for all simulations. This leads to an optimum utilization of the dynamic range and thus an improved noise performance, depending on α and β. This should be noted as a difference to the simulations described in [12, 13].

The demodulator threshold Θ for the detector was determined for each modulation code and for each σ_n separately. It was selected to minimize p_e. The simulation length for each point was chosen long enough to take into account at least 100 bit errors in the computation of each p_e value.

4.2 Simulation Results

The simulation results are given in Figures 3 to 6 for the uncoded case as well as the above-mentioned modulation codes. The simulated bit error rate p_e is plotted over the noise standard deviation σ_n.

For the uncoded case (Figure 3) and the evaluated modulation codes (Figures 4 to 6), lower error rates p_e can be observed for larger grid spaces d. Clearly, this is due to the reduced amount of interference at larger grid spaces d. Furthermore, p_e decreases for smaller noise standard deviations σ_n in all simulations.

Compared to the uncoded case, all codes significantly improve the bit error rate p_e. It is obvious that the $(4,4;8;2,2)$ and $(3,3;4;2,3)$ codes perform much better compared to the $(3,3;6;3,2)$ code but also require lower code rates r_m. It can be observed that the $(4,4;8;2,2)$ code with $r_m = 1/2$ performs in many cases better than the $(3,3;4;2,3)$ code with rate $r_m = 4/9$ despite of its slightly higher code rate. However, note that the X bit of the $(3,3;4;2,3)$ code can be additionally used for error detection. This capability has not really been exploited in our p_e statistics, which explains that we found the $r_m = 1/2$ code partially outperforming the $r_m = 4/9$ code.

In the following, a bit error rate $p_e = 10^{-2}$ without modulation coding for $d = 6\,\mu$m is assumed. Practical experiments have shown that this is a realistic magnitude for p_e, and such an error rate can be easily drawn to about 10^{-6} by application of a $r = 1/2$ forward error correction code. According to Figure 3, these values correspond to a noise standard deviation $\sigma_n \approx 0.13$. Assuming the $(4,4;8;2,2)$ code from Figure 6, this leads to an improved error rate of $p_e \approx 2 \cdot 10^{-3}$. Even a smaller grid space of $d = 5\,\mu$m is possible to approximately satisfy $p_e \leq 10^{-2}$. A grid space $d = 4\,\mu$m leads to $p_e \approx 5 \cdot 10^{-2}$ which is already larger compared to the uncoded case with $d = 6\,\mu$m.

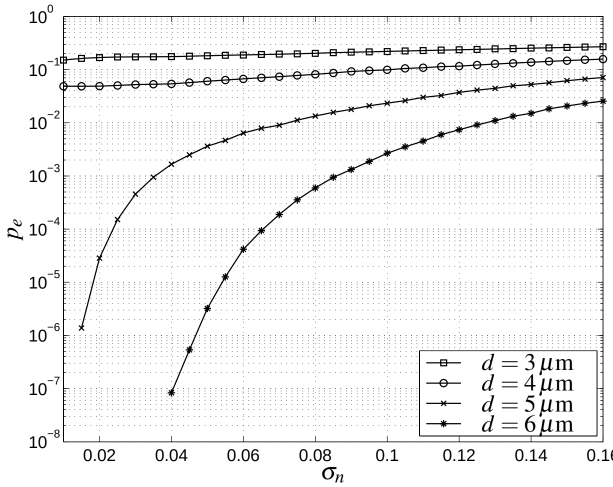

Figure 3. *Bit error rate p_e vs. σ_n for different grid spaces d without modulation coding, code rate $r_m = 1$.*

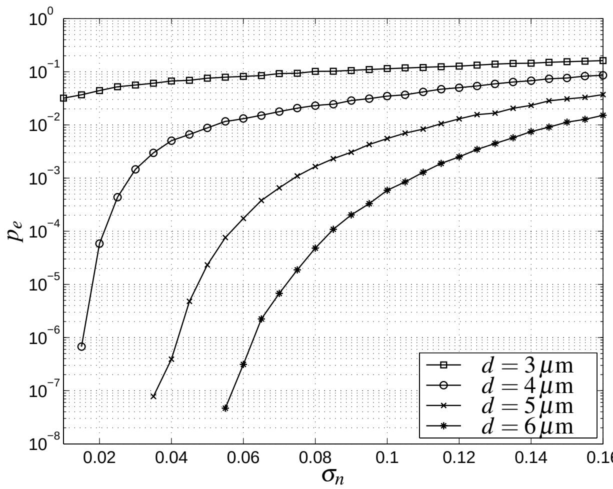

Figure 4. *Bit error rate p_e vs. σ_n for different grid spaces d and $(3,3;4;2,3)$ modulation coding, code rate $r_m = 4/9$.*

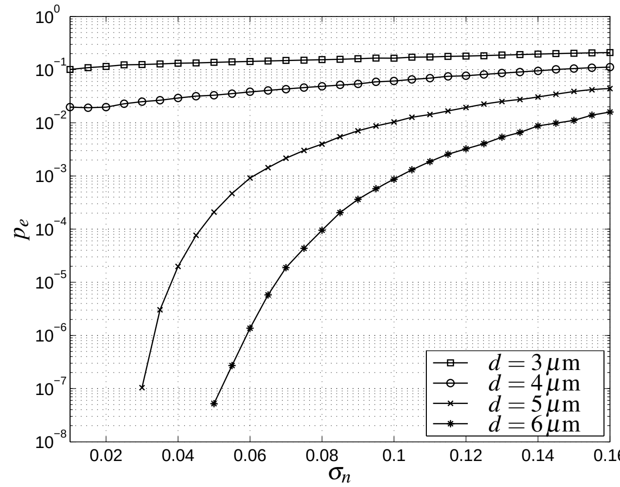

Figure 5. *Bit error rate p_e vs. σ_n for different grid spaces d and $(3,3;6;3,2)$ modulation coding, code rate $r_m = 2/3$.*

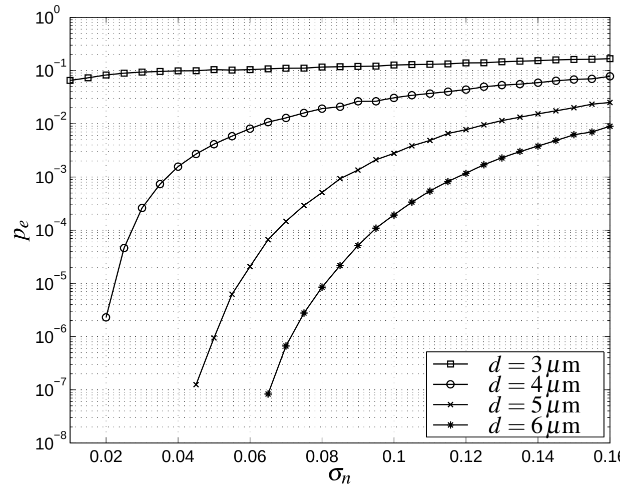

Figure 6. *Bit error rate p_e vs. σ_n for different grid spaces d and $(4,4;8;2,2)$ modulation coding, code rate $r_m = 1/2$.*

To analyze the impact on the storage capacity without regarding error correction coding, the error probability $\tilde{p}_e$ is defined that is achieved through modulation coding in combination with the grid space $\tilde{d}$. The values p_e and d are assumed for the uncoded case. Due to the dependencies defined in (6), a capacity gain can be achieved *if and only if*

$$r_m > \left(\frac{\tilde{d}}{d}\right)^2 \tag{11}$$

is satisfied, while

$$\tilde{p}_e \leq p_e \quad . \tag{12}$$

It may be helpful for understanding the implications on the grid space, to transform (11) into

$$\sqrt{r_m} \cdot d > \tilde{d} \quad . \tag{13}$$

For the above-mentioned case ($r_m = 1/2$ and $d = 6\,\mu$m) it follows that $\tilde{d} < 4.24\,\mu$m would be necessary to achieve a capacity gain. Regarding the next integer grid space ($d = 4\,\mu$m) in Figure 6, it becomes clear that for $\sigma_n = 0.13$ the above-stated condition (12) is not satisfied ($\tilde{p}_e \approx 5 \cdot 10^{-2} > p_e = 10^{-2}$) and hence no capacity gain is achieved. Due to (13), a code with at least the same error performance and code rate $r_m > 0.7$ would be necessary to achieve a capacity gain. Hence, the code rate $r_m = 1/2$ for the $(4,4;8;2,2)$ code is too small in order to justify its use and a smaller grid space d should be favoured instead. Similar considerations also lead to no capacity gains for the $(3,3;6;3,2)$ code with $r_m = 2/3$ and the $(3,3;4;2,3)$ code with $r_m = 4/9$, which is a surprising and interesting result.

5. Conclusions

The aim of our work was to find out, if a set of fixed-length modulation codes can lead to an overall storage capacity gain for digital data storage on microfilm. Therefore, the focus was on the tradeoff between the code rate r_m of the modulation code and the grid space d. Simulations based on real system parameters have been performed to discuss possible tradeoffs.

It turned out from the simulations that for the assumed realistic parameters, none of the regarded codes actually leads to a capacity gain. Obviously, the code rates of the employed modulation codes are still too small, and hard decision decoding of the modulation codes is surely suboptimal, especially if means of forward error correction are used in addition. However, further investigations should consider error correction coding and may also include large-scale practical tests or an improved channel model for data storage on microfilm. Besides the storage capacity aspects, it should also be considered that smaller grid spaces also require higher resolutions and thus more complex reading devices. Concluding all these facts, the use of the investigated codes is questionable or even not advisable for digital data storage on microfilm.

Acknowledgments

This work was funded by the German Federal Ministry of Economics and Technology (BMWi) within the project MILLENIUM. We thank our colleagues at Fraunhofer Institute for Physical Measurement Techniques (IPM) in Freiburg, Germany, for the exposure of several test films.

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