Parallel data detection in page-oriented optical memory

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We discuss a novel two-dimensional parallel technique for reliable data detection in page-oriented optical memories. The method is motivated by decision feedback techniques and is fully parallel, offering convenient, locally connected electronic implementation. The algorithm is shown to offer significant improvements over simple threshold detection and in some cases can approach the maximum-likelihood bound of data reliability. © 1996 Optical Society of America

A great deal of attention has been paid recently to optical storage and in particular to volume optical storage in the hope of achieving high capacity, short access time, and a large sustained data rate. An important characteristic of these volume optical storage systems is their use of parallel page access. Such two-dimensional (2D) data access takes advantage of the natural parallelism of optical systems and facilitates high aggregate data rates. Owing to the nature of page access, the interface to page-oriented optical memory must support this high degree of parallelism when carrying out tasks such as detection (i.e., decision making) and decoding (i.e., error correction).

In this Letter we focus on the problem of reliable data detection and present a simple parallel algorithm for realizing improved detection performance in the presence of 2D intersymbol interference (ISI) and noise.

The problem of reliable data detection is complicated by imperfect channel characteristics. Volume optical memory represents a particularly challenging channel with many noise types and a variety of other sources of imperfection, such as misalignment, nonuniform illumination, and magnification error. Cross-talk noise, or interpage interference, has been studied in this context, and some preliminary discussion of ISI in volume holographic systems has also taken place. 2D ISI is analogous to the one-dimensional serial case arising from the low-pass nature of the optical system transfer function in two dimensions. The blur resulting from this low-pass behavior causes neighboring bits in a data page to overlap, complicating the resulting detection problem. Simple techniques for mitigating ISI in two dimensions can be developed that are analogous to the one-dimensional serial case, and these include partial response coding, gray-scale modulation codes, and sequence detection (e.g., the Viterbi algorithm).

In this Letter we present a simple 2D parallel detection method that is motivated by optimum filtering and decision feedback techniques and is suitable for page-oriented optical memory.

ISI in a 2D optical channel can be characterized by the point-spread function (PSF) of the system. We model the discrete PSF in the intensity domain as a $(2K + 1) \times (2K + 1)$ array, $H = \{h(i, j)\}$. The input data page (i.e., the data to be stored) is represented by the $N \times N$ intensity array $P = \{p(i, j)\}$ and the received intensity array (i.e., the data measured at the CCD), $R = \{r(i, j)\}$, is given by the convolution

$$r(i, j) = \sum_{m=-K}^{K} \sum_{n=-K}^{K} h(m, n) p(i - m, j - n).$$

We take the input data page to be binary valued so that $p(i, j) \in \{0, 1\}$. Although this model is directly applicable to an incoherent imaging configuration, we can make it valid for coherent memory systems by defining the PSF in terms of field. A squaring operation is then required following the convolution filter. To connect the continuous-space domain of the optical system to this discrete channel model, we establish a detector array geometry in which the detectors are square with side $s = 1$ and separation $d$ normalized to $s$. We compute the values of the discrete PSF based on the use of a radially symmetric Gaussian blur with width $\sigma_b$:

$$h(i, j) = \int_{-d/2}^{d/2} \int_{-d/2}^{d/2} \exp[-(x^2 + y^2)/2\sigma_b^2] \, dx \, dy.$$

For a Gaussian blur function, the resolution limit (Sparrow limit) is achieved for $\sigma_b = 0.5$, and the corresponding values of the discrete PSF are given by $h(0, 0) = 0.466$, $h(-1, -1) = h(1, -1) = h(-1, 1) = 0.025$, and $h(0, 1) = h(1, 0) = h(0, -1) = h(-1, 0) = 0.107$, where the values of $h(i, j)$ have been normalized according to $\sum_{ij} h(i, j) = 1$.

In a data page comprising ones and zeros, a large Gaussian blur can give rise to erroneous detection owing to (1) an increase in the received zero signal level arising from neighborhood cross talk and (2) a loss of signal power in the one signal level. The effect of ISI is exacerbated by the presence of noise. Page-oriented optical memory systems suffer from both Gaussian (e.g., thermal) and non-Gaussian (e.g., shot and interpage interference) noise. Here we focus on the performance of detection algorithms in the presence of Gaussian noise only. We model the noise process after conversion from the optical to the electrical domain. In this case the measured signal appears as a current or voltage and is represented by the data array

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A = \{a(i, j) = r(i, j) + n(i, j)\}, where \(n(i, j)\) is taken to be a white-noise process with a Gaussian probability-density function characterized by its mean (\(\mu = 0\)) and variance \(\sigma_n^2\). The signal-to-noise ratio (SNR) of the electrical signal can be defined as

\[
\text{SNR} = \frac{2E[r^2(i, j)]}{E[n^2(i, j)]},
\]

\[
= \sum_{ij} h^2(i, j)/\sigma_n^2,
\]

where \(E[]\) represents the expectation operator and the assumption of independent, identically distributed data has been made. Two useful bounds on the performance of data-detection paradigms can be defined. A worst-case bound is found by use of a fixed threshold detection process. Given knowledge of the channel PSF, we can define this threshold by including the average effects of ISI. Such a fixed threshold is given by

\[
\text{TH} = [E[r(i, j)|p(i, j) = 1] + E[r(i, j)|p(i, j) = 0])/2,
\]

where for \(K = 1\) the expectation operator \(E[]\) averages over all possible data patterns that may appear at the eight nearest neighbors of pixel \(p(i, j)\). Figure 1 shows the probability of detection error as a function of SNR for various detection methods using a Gaussian blur with \(\sigma_b = 0.623\) and a page size of 128 \(\times\) 128 pixels. This channel is operating just beyond the Sparrow resolution limit. The performance of the worst-case bound is shown as curve TH in the figure. A simple threshold detector is seen to be a very poor decision paradigm for this ISI case, because a large probability of detection error occurs even for a high SNR. The best-case bound on detection performance is obtained in the limit of pagewise joint detection. A simple way to envisage such a scheme is by means of a very large (e.g., \(2^{N^2}\)) elements look-up table with entries corresponding to all possible received pages in the presence of ISI. Such a procedure is, of course, not feasible in practice; however, its performance represents the maximum-likelihood detection solution and can be approximated by curve ML in Fig. 1.\(^5\)

A simple technique for improving the performance of a single threshold detector is the use of a Wiener filter.\(^10\) This filter operates on the received signal to approximate an inverse channel within the constraints of minimum noise and finite support. An exact inverse is in general not feasible owing to (1) the existence of zeros (or very small values) in the channel transfer function and (2) the need for an unacceptably large number of filter taps (i.e., infinite impulse response filtering). Thus the finite support constraint ensures that the implementation of the filter remains tractable. We designed Wiener filters for the channel corresponding to \(\sigma_b = 0.623\) at various values for the SNR. These filters were followed by simple threshold detection, and their performance is represented in Fig. 1. A 3 \(\times\) 3 filter (curve W3) is seen to offer significant improvement in performance compared with the threshold alone, and the use of a 5 \(\times\) 5 filter (curve W5) exhibits even greater improvement. Wiener filters with larger support exhibited no further improvement. This characteristic makes the parallel hardware implementation of such a filter attractive owing to the locally connected nature of the required processing.

The Wiener filter discussed above is utilized in conjunction with a simple threshold decision rule. It is possible to replace this threshold-based decision paradigm with a simple iterative decision-making process. We have developed such a 2D parallel iterative procedure for data detection. This method is motivated by decision feedback techniques used in conventional serial communication channels. The method operates on a received page in parallel. The first step of the algorithm is to apply the fixed threshold (TH) to the received page, producing a data estimate \(\hat{p}(i, j)\). At each pixel on the page, a test is performed based on these estimated data. Consider pixel \(p(i, j)\). It is possible that \(p(i, j) = 1\), so this pixel is set to one and its neighborhood as determined by \(\hat{p}(i, j)\) is used to convolve with the optical-system PSF to obtain a corresponding estimate of the received pixel \(\hat{r}(i, j)\), where the subscript indicates that this estimate is conditioned on the assumption that \(p(i, j) = 1\). In a similar way, \(\hat{r}(i, j)\) is produced, conditioned on \(p(i, j) = 0\), and whichever hypothesis best matches the actual received data is taken as the updated estimate. That is, if \(|\hat{r}(i, j) - a(\hat{i}, \hat{j})| < |\hat{r}(i, j) - a(i, j)|\), then \(p(i, j) = \hat{p}(i, j)\) for the next iteration. Because this procedure is executed simultaneously at all pixels on the page, all updates to \(\hat{p}(i, j)\) take place simultaneously during each iteration. This procedure is continued until no further change takes place in the array \(\hat{p}(i, j)\).

When the simple Wiener filter is followed by this parallel iterative procedure, the detection performance improves as shown in Fig. 1. The figure shows both the 3 \(\times\) 3 and 5 \(\times\) 5 Wiener filters followed by two stages of the parallel decision algorithm in curves W312 and W512, respectively. Although the performance of the algorithm does not depend directly on page size \(N^2\), the convergence of the iterative procedure does. We have found, however, that for page sizes as large as

\[\text{Page Size } = 128 \times 128\]

\[\text{BER} \quad 10^{-10} \quad 10^{-15} \quad 10^{-20} \quad 10^{-25} \quad 10^{-30} \quad 10^{-35} \]

\[\text{SNR (dB)} \quad 10 \quad 20 \quad 30 \quad 40 \quad 50 \quad 60 \]

\[\text{TH} \quad \text{W3} \quad \text{W5} \quad \text{W312} \quad \text{W512} \quad \text{ML} \]

Fig. 1. Probability of detection error (bit-error rate, BER) versus SNR for various data detection techniques. Gaussian blur parameter \(\sigma_b = 0.623\).
128 × 128, 86% of our trials have converged after two iterations. For this reason, all the simulation data presented here utilized a fixed termination condition of two iterations. This characteristic makes possible an efficient hardware implementation of the algorithm whose operation can be viewed as a pagewise two-stage data pipeline. Alternatively, the algorithm can be implemented as a time-multiplexed pipeline requiring only two clock cycles. More important, such an implementation is locally connected owing to the small support of the optical PSF (i.e., small \( K \)).

Figure 1 depicts the ability of simple parallel decision procedures to detect binary-valued data reliably in the case of severe optical blur. These data represent a channel operating beyond the Sparrow resolution limit and can be considered a novel approach to superresolution. In a system with less severe optical blur, operating within the resolution limit, the performance of our parallel technique more closely approaches the maximum-likelihood performance bound. In Fig. 2 we show the performance of these various detection techniques for a channel with \( \sigma_b = 0.45 \). Curves W3 and W5 are nearly identical to curves W512 and W312; however, the iterative procedure is seen to offer considerable improvement compared with the Wiener filter alone. This performance is approaching the lower bound on bit-error rate (curve ML). It is possible for this channel for one to compute the memory capacity gain that is achieved with the W512 technique as compared with a single threshold decision rule (TH). Consider an angularly (or wavelength) multiplexed volume holographic optical memory (e.g., photorefractive) requiring a maximum bit-error rate below \( 10^{-4} \). The minimum SNR’s required for the TH and the W512 algorithms can be found in Fig. 2 and are 29.5 and 18.2 dB, respectively. In the case considered here, the Gaussian noise probability-density function suggests a system dominated by fixed noise sources, in which case the SNR decreases with the number of stored pages \( (M) \) as \( \text{SNR} = \gamma / M^2 \), where \( \gamma \) is a constant that depends on various aspects of the optical system. In such a case, the difference in minimum SNR between these two detection schemes corresponds to a difference in the maximum allowed number of stored pages. In this example, the capacity gain arising from the use of W512 is 267%.

We have presented a novel 2D parallel technique for reliable data detection within page-oriented optical memory systems. This method is motivated by decision feedback techniques and is fully parallel, offering a convenient, locally connected electronic focal-plane implementation. The algorithm has been shown to offer significant improvements over simple threshold detection and in some cases can approach the lower limit on data reliability. These and other data-detection techniques will be useful for extending the usable capacity of volume optical memory.

References