PROCEEDINGS

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FOREWORD

The Twenty-Sixth Annual Allerton Conference on Communication, Control, and Computing was held at Allerton House, Monticello, Illinois on September 28-30, 1988. The conference was sponsored by the Coordinated Science Laboratory and the Department of Electrical and Computer Engineering at the University of Illinois at Urbana-Champaign. These *Proceedings* contain the papers presented at the Conference.

We are grateful to Professor Jack Keil Wolf of the University of California at San Diego for his plenary lecture "New Results for Magnetic and Optical Recording Channels." We would like to thank all of the session chairpersons and the authors for their contributions.

We appreciate the support of Professor M.E. Van Valkenburg, founder of the series of Allerton Conferences, Professor T.N. Trick, Head of the Department of Electrical and Computer Engineering, and Professor W.K. Jenkins, Director of the Coordinated Science Laboratory. We would also like our colleagues Professors J.A. Abraham, K. S. Arun, P. Banerjee, M.T. Basar, Y. Bresler, D.J. Brown, W.K. Fuchs, T.S. Huang, R. Iyer, P.V. Kokotovic, P.R. Kumar, H. Lee, M.C. Loui, J.V. Medanic, D.C. Munson, J.H. Patel, W.R. Perkins, K.R. Poolla, H.V. Poor, F.P. Preparata, M.B. Pursley, V. Ramachandran, D.V. Sarwate, and B.W. Wah for their generous assistance in reviewing papers (over 360 were submitted) and organizing the accepted papers into sessions. A special thanks goes to Professor G. Manacher at The University of Illinois at Chicago for his assistance to the program committee.

We are grateful to Mr. Steven Williams for his handling of the business affairs of the Conference, to Mr. Robert Ebeling and his assistants for their timely printing of large numbers of programs and registration packets, to Jennifer Eickman and her assistants at the Allerton House who cheerfully accommodated our group, and especially to Ms. Dixie Murphy, Ms. Janet Reese, Ms. Lila Rhoades, and Ms. Sharon Teuben-Rowe for their capable assistance in handling the Conference announcement, registration, program preparation, and editing and sales of these *Proceedings*. These individuals make the Conference co-chairmen look good by doing most of the work. Finally, we would like to thank Ms. Christina Kamra of John Wiley for sponsoring a coffee break and book display.

M.W. Spong

B. Hajek

TABLE OF CONTENTS

II-D: ADAPTIVE AND ARRAY SIGNAL PROCESSING

Chairman: W. K. Jenkins
University of Illinois at Urbana-Champaign

II-E: INFORMATION THEORY AND CODING

Chairman: D. L. Snyder
Washington University

III-C: IMAGE PROCESSING AND ANALYSIS

Chairman: Yoram Bresler
University of Illinois at Urbana-Champaign

III-D: DISTRIBUTED COMPUTATION AND COMPLEXITY THEORY

Chairman: M. C. Loui
University of Illinois at Urbana-Champaign

III-E: TESTING AND CONCURRENT ERROR DETECTION

Chairman: J. Patel
University of Illinois at Urbana-Champaign

IV-A: COMBINATORIAL ALGORITHMS

Chairman: C. L. Liu
University of Illinois at Urbana-Champaign

IV-B: CONTROL SYSTEMS DESIGN

Chairman: S. H. Zak
Purdue University

IV-E: ALGORITHMS AND ARCHITECTURES FOR SIGNAL AND IMAGE PROCESSING

Chairman: Hua Lee
University of Illinois at Urbana-Champaign

AN OPTIMUM SEQUENCE ESTIMATION APPROACH IN THE ABSENCE OF SYNCHRONIZATION

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ABSTRACT

A dynamic programming algorithm for joint maximum-likelihood estimation of sequences and symbol timings is introduced. The algorithm, which makes use of easily computed data, is easily implementable, extremely robust to timing-errors and alleviates, the need for a symbol synchronizer, which in general requires the complete sample-path to produce its timing estimates.

I. INTRODUCTION

In digital communication systems, an important and integral part of every practical receiver is the symbol synchronization subsystem. The function of the symbol synchronizer is to dictate to the receiver *where* in time the symbols are located. The receiver, subsequently, utilizes this timing information as if it were *perfect* in order to compute its decision statistics and decide *what* the transmitted symbols are. Clearly, this timing information is essential to the receiver and, if inaccurate, the effect could, and often is, catastrophic on system performance.

Extensive work on describing the performance degradation due to imperfect timing information has been done in the past and can be found, for example, in the excellent books of Lindsey and Simon [1] and Stiffler [2]. Results reported in these two references indicate that essentially disastrous results are obtained when the standard deviation of the timing jitter exceeds some small value. The severe performance degradation is due to the contamination of the decision statistics by adjacent symbols as a result of imperfect timing, -effectively reducing the signal-to-noise ratio- and because the receiver makes decisions assuming that the timing information is perfect. This assumption is in general not valid and leaves the receiver defenseless in the presence of, possibly, large timing-errors. We will see later in this paper that a receiver designed to make decisions in the presence of timing-errors has significant performance advantages over conventional receivers that rely blindly on the synchronization subsystem to provide timing information. Other approaches to the synchronization problem of interest can be found in [10].

II. ALGORITHM DERIVATION

In this section a dynamic programming algorithm for delay estimation and joint delay and sequence estimation is derived for a Gaussian channel and binary, antipodal signaling. Similar algorithms for other modulation schemes and for an optical Poisson channel can be found in [11].

We have the following communication problem

$$r(t) = \sum_{j=-\infty}^{\infty} S_j(t) + n(t), \tag{1}$$

where $S_j(t) \in \{S(t), -S(t)\}$, $(j-1)T \leq t \leq jT$ is one of two antipodal modulation signals chosen independently and with equal probability and

$$\int_0^T S^2(t)dt = E.$$

Under our white Gaussian noise assumption, $n(t)$ is zero-mean, white Gaussian noise with spectral density $N_0/2$.

Not having a timing reference, the receiver computes sequentially the following statistics

$$r_j = \frac{1}{E}\int_{(j-1)T}^{jT} r(t-\tau')S(t)dt, \quad j = 1, 2, \cdots, N, \cdots \quad , \tag{2}$$

where, $\tau' \in [0, T)$ is the timing-error, as shown in Figure 1. Obviously, if $\tau' = 0$, the statistics $\{r_j, j = 1, 2, \cdots, N, \cdots\}$ constitute a sufficient statistic for the sequence estimation problem. In the presence of timing-error, however, although the r_j clearly contain information about the transmitted sequence, they are not a sufficient statistic and, thus, decisions based on them are not globally optimal. On the other hand, computing the statistics r_j requires very little complexity and, as we will see later, the performance obtained based on these statistics can be significantly better than the performance of conventional receivers utilizing a separate synchronizer.

The problem we address in this paper is that of optimally estimating sequences of symbols and the timing-error from the incomplete statistics $\{r_j, j = 1, 2, \cdots\}$. We begin by deriving a likelihood function of the observed data conditioned on the timing-error τ' and the modulation sequence.

Let $\mathbf{r} = (r_1, r_2, \cdots, r_N)$ be the vector containing the computed statistics r_j, $j = 1, 2, \cdots, N$ and $\mathbf{x} = (x_1, x_2, \cdots, x_{N+1})$, $x_i \in \{1, -1\}$, be the modulation sequence resulting in the received vector $\mathbf{r}$. The elements of $\mathbf{r}$ are conditionally independent, Gaussian random variables with mean

$$E[r_j/\mathbf{x}, \tau'] = x_j \frac{1}{E}\int_0^{\tau'} S(t)S(t+T-\tau')dt + x_{j+1}\frac{1}{E}\int_{\tau'}^{T} S(t)S(t-\tau')dt \ . \tag{3}$$

The variance of each r_j conditioned on the timing-error τ' and the modulation sequence $\mathbf{x}$ is

$$VAR[r_j/\mathbf{x}, \tau'] = N_0/2E, \tag{4}$$

independently of j. Assuming rectangular pulses $S(t)$ and letting

$$\tau = \frac{1}{E}\int_0^{\tau'} S(t)S(t+T-\tau')dt = \frac{\tau'}{T} \tag{5}$$