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THE STUDY OF SYNCHRONIZATION TECHNIQUES FOR OPTICAL COMMUNICATION SYSTEMS

First Quarterly Report
Covering Period of 1 December 1968 to March 1969

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This document represents the first quarterly report of a NASA Research Program to study synchronization techniques for optical communication systems. The work is being carried out at the Electrical Engineering Department at the University of Southern California, under NASA Contract No. NGR-05-018-104, with Professor R. M. Gagliardi as principal investigator. This grant is part of the research program at NASA's Electronics Research Center, Cambridge, Massachusetts.

This report indicates the organization of the research activity and lists the tasks presently being studied. The research effort is primarily analytical in nature, and is divided into two categories. The first involves tasks with direct application to the synchronization problem, while the second involves related areas also being studied under the grant. This document reports technical progress during the first quarter, but detailed results will be published in separate interim reports, and are omitted here.

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Synchronization

1.1 Introduction

Synchronization between receiver and transmitter in a coherent communication system basically requires the ability to time lock a receiver signal generator with a received synchronizing waveform from the transmitter. The noise-free signal from the generator can then be used for all necessary timing operations at the receiver. This locking operation is typically performed by using a tracking loop to generate a timing error, which drives the local signal generator into proper synchronism. If a sin wave (pure tone) is used as the synchronizing signal the tracking loop is a phase-locked loop, while periodic digitally coded signals require digital correlation tracking loops. Any synchronizing system can operate either in a "pure" or "impure" locking mode. In the former, the sync system operates only upon the synchronizing signal (except for additive noise) in attempting to obtain lock. In "impure" synchronization, the locking is obtained by operating upon a sync signal immersed within the desired data. Although pure synchronization is most desirable, the transmitter must allocate a portion of its bandwidth and power in order to transmit the synchronizing signal in addition to the data. In impure synchronization this excess allocation is not necessary, but sync operation is hindered by the presence of the data. In present day microwave communication systems both methods have been successfully employed. In pure synchronization, the sync signal is generally separated (multiplexed) from the data, either in frequency or time, and tracked independently of the data. Impure synchronization methods have been used extensively in PSK data transmission, in which "Costas" tracking loops and "squaring" loops have been used to ferret out the sync information from the data modulation before locking.

The synchronization procedure basically requires two somewhat independent operations - acquisition and tracking. In acquisition, the receiver locking signal must be first time oriented so that the loop can generate a useable error for

"pulling in" the received synchronizing signal. Once the proper error signal has been generated, the loop will act to lock in the timing signal; i.e., the signal has been "acquired". After acquisition, the synchronizing system must continue to operate in order to maintain the locked condition in spite of synchronization anomalies (time shifts due to relative motion, oscillator jitter and drift, etc.). That is, the loop must continually track the repetitive synchronizing signal during the presence of these anomalies in order to maintain coherent operation.

The choice of synchronizing signals plays an important role in the design of a synchronization subsystem. This is due to the fact that ease of initial acquisition and "tight" tracking (good resolution in timing) are somewhat conflicting requirements. Basically, sync signals with large bandwidths yield good resolutions, but narrow band signals are easier to acquire.

1.2 Synchronization of Optical Communication Systems

An optical communication system will require timing and synchronization, and therefore the procedures previously stated are necessary as in any microwave link. In addition the properties of optical radiation and the higher frequencies involved introduce further characteristics that distinguish the optical synchronization problem from that at microwaves. In optical communication systems the accepted method for signal transmission are either a) intensity modulation of an optical source, followed by direct photo-detection at the receiver, or b) modulating (AM, FM, or PM) a monochromatic source and using heterodyning detection at the receiver. Recently, the advantages of a pulsed PPM optical system using direct detection have been reported [1-4], and it appears that this technique may evolve as the primary mode of PCM transmission when optical power is at a premium. Although system performance has been shown [3-4] to improve as the pulses are made extremely narrow, the synchronization requirements simultaneously become more severe. For this reason particular emphasis in this present study effort will be devoted to problems endemic to this mode of operation.

1.3 Pure Synchronization with Direct Detection

The most basic synchronization operation that may be considered would be pure synchronization of an intensity modulated tone by a phase lock loop following direct detection. The output of the photo-detector is a shot noise current process, whose statistics and properties have been well documented. Although a plethora of literature is available in phase lock loop theory, the behavior of such a device in the presence of shot noise input has not been rigorously investigated. One of the first principle tasks in this study was the analysis of phase locking in this mode of operation. Since the synchronizing signal is immersed in a rather complicated way within the shot noise, the use of previous results for synchronizing in additive noise are in general not applicable. In addition, the loop behavior may be further complicated by thermal noise, dark currents, photo-multiplier effects, and background radiation. At this point attention has been primarily devoted to determining the statistics of the tracking error for a first order tracking loop, when driven by shot noise of known intensity. It is felt that adequate understanding of this first order system could be later extended to higher order loops in a fairly straight forward manner. The following results for the first order loop have been derived, and will appear in a forthcoming technical report.

1) The differential equation for the steady state probability density of the tracking error with poisson shot noise inputs has been shown to be a Kolgomorov partial differential of infinite order.

2) The coefficients of this equation decrease rather quickly with the intensity of the synchronizing signal (more specifically, with the sync signal "denseness" - the number of synchronizing photo-electrons in the reciprocal of the tracking loop bandwidth)

3) For high intensities the Kolgomorov equation approaches the Fokker-Planck partial differential equation (i. e. the first two coefficients of the infinite order equation tend to dominate). The steady state solutions of the Fokker-Planck Equation is known, and therefore the probability density of the tracking error can be stated for the high intensity case. This result can be related to the

result for addi tive gaussean noise if the proper definitions of variables is made.

4) The solution for the high intensity case has been examined, and the steady state probability density of the tracking error has been explicitly stated. The effect of background radiation and additive thermal noise has been included. The mean square tracking error has been computed for this density, as a function of the design parameters of the system.

Present study is continuing in this area and is devoted to:

1) Attempting to solve the third order Kolgomorov equation, hopefully to obtain a correction term to the previous high intensity result. This would be particularly significant in our study since it would indicate how performance is degraded as the synchronizing signal intensity is decreased.

2) Attempting to derive results for the digital sync signal case. It appears at present that similar results can be stated for this as with the phase lock loop.

1.4 Pure Synchronization With Heterodyne Detection

The problem to be investigated in this case consists of phase locking, or correlation tracking, after heterodyning an optically coherent signal. Analytically, the problem differs from that previously stated in that a) the counting statistics after heterodyning are not in general poisson. The actual density for the photo-election count after heterodyning has not been written in closed form, although the moments of the process can be derived. b) The spatial characteristics of the impinging radiation field over the optical detector surface, which affects the strength of the demodulated signal, must be incorporated into the analysis. c) The effect of phase and amplitude distortion of the optical beam during transmission must be considered if the synchronizing signal has been phase modulated onto the optical carrier. A closely related problem is that of phase locking the local laser. That is, using the phase error information at the heterodyne frequency to control the phase of the local laser used for heterodyning. Although time locking is not necessary for optical heterodyning, such a system would have capability of tracking optical doppler changes and improving RF detection.

1.5 Pure Synchronization With Pulsed Lasers

The requirement for pulsed laser operation places a constraint on the synchronization system that eliminates the flexibility of system design as to the choice of synchronizing signals. Furthermore, the generation of error signals when extremely narrow synchronizing pulses are used introduces a difficult design problem. If the received sync pulses are extremely high powered, the direct detected signal may be used in its raw form for subsequent synchronization. However, when the noise effects are not neglegible the synchronizing system must recover the timing information from the noisy pulses. In this case it appears that, after direct detecting a pure sync pulse stream, a form of early and late gate tracking (often called split gate tracking) is the easiest to implement, although there may be some advantages of a more complicated correlating signal. This area will be further examined in the present study effect.

Since the tracking loop will operate "electronically" the loop response will not be as fast as the optical pulse width. It appears therefore that it is unnecessary to use optical sync pulses narrower than the loop response time. The narrow optical pulse, since they represent large bandwidth signals, can be used to derive good resolution in timing but are difficult to initially acquire. Alternate schemes that make use of the harmonic content of the optically detected pulses may yield a suitable compromise of resolution and acquisition.

1.6 Impure Synchronization With PPM Systems

In optical PPM systems synchronization can be obtained without the necessity to transmit separate sync pulses. In PPM, optical pulses are position modulated to achieve PCM data word transmission. Although the pulse position changes from word interval to word interval according to the data, the presence of a pulse in each interval implies the existence of signal energy at the word rate frequency, which may be used for impure synchronization. After proper filtering, the word rate frequency may be extracted to achieve lock-up, although the data modulation will tend to hinder the operation. Present study

is attempting to determine the ability to acquire synchronization in this environment.

1.7 Effect of Tracking Errors on Error Rates in PPM Systems

In previous literature [3, 5], error probabilities have been derived for M-ary PPM optical communication systems. The primary assumption in the derivation is that the receiver can "count photons" over the exact interval in which the optical pulse was transmitted, this is equivalent to an assumption of exact synchronization between transmitter and receiver. When imperfect synchronization is present, the receiver does not count photons over the exact signalling interval. This causes a decrease in the number of signal photons, with a proportionate increase in photons in adjacent non-signolling intervals. The overall effect is a two-fold decrease in optical signal to noise ratio, since the background photon rate is assumed constant. An initial objective is to attempt to assess the corresponding degradation in error rates by modifying earlier results to account for timing errors. Using the results of Section 1.3 it is hoped that an average over the statistics of the typical timing error can be made, so that the previously reported error rates can be replotted in terms of the tracking parameters of the synchronizing system.

1.8 Synchronization as an Estimation Problem

The use of tracking loops for the maintainance of synchronization was presented as a somewhat ad hoc procedure for acquiring synchronization. A more academic approach is to consider the phase or time delay of the received sync signal as an unknown parameter that is to be optimilly estimated by the synchronizing subsystem. The formulation of the synchronization problem for an optical system in this context is presently under study. A preliminary result that is somewhat significant, and yet not intuitive, is that with pure tone synchronizing signals and maximum aposteriori estimation, the optimal tracking device is not the standard phase lock loop. The result does specialize to this, however, under certain conditions; in particular, high signal intensity,

Study in Related Areas

2.1 Properties of Shot Noise Processes

A study effort has continued in the attempt to clearly analyze the shot noise process following optical photo-detection. Since the intensity of the radiation becomes the intensity of the shot noise process, the problem is basically that of relating the statistics of the shot noise, to the statistics of its inherent intensity. Some results have been obtained when the shot noise is governed by poisson countering statistics (i.e., poisson shot noise) and are reported in the publication:

"On the Representation of a Continuous Stochastic Intensity by Poisson Shot Noise"
Authors - R.M. Gagliardi - S. Karp
USCEE Technical Report No. 334 March 1969

ABSTRACT

In many applications a poisson shot noise (PSN) process is said to statistically "represent" its intensity process. In this paper an investigation is made of the relationship between a PSN process and its intensity, when the latter is a sample function of a continuous stochastic process. The difference of the moments and the mean square difference between the two processes is examined. The continuity assumption on the intensity permits the development of a sequence of moment relationships in which the effect of the PSN parameters can be seen. The results simplify, and afford some degree of physical interpretation, when the component functions of the PSN are "rectangular", or when the intensity process does not vary appreciably over their time width. An integral equation is derived which defines the component function that minimizes the mean square difference between the two processes. It is shown that a "degenerate" form of component function induces complete statistical equality of the two processes. The problem has application to optical communication systems using photodetectors.

The results of this report are significant in that they indicate the conditions and manner in which the shot noise statistics are related to those of the intensity. In addition, the results tend to justify earlier work [6] involving modelling of optical radiation by poisson shot noise processes. The component functions of the shot noise were assigned physical meaning as wave packets. The most important application of this model is in the statistical analysis of scattering of optical radiation. By describing the behavior of the "wave-packets" in channels of this type the statistics of the radiation field and its intensity can be examined. Once these are known, the statistics of the photo-electron count following photo-detection can be determined.

2.2 Optimal Optical Detection and Filtering

There are three particular problem areas under this topic that are or will be investigated.

1) Deriving optimal mean square filters for shot noise processes imbedded in additive Gaussian noise.

2) Deriving optimal spatial filters and detectors for the reception of an optical radiation field.

3) Continuing attempts to prove the universal optimality of the pulsed intensity set in an M-ary optical digital communication system. The result has been proven for M=2 (binary systems) and for any M at asymptotically low signal to noise ratios [3]. This universal optimality has often been conjectured, but never proven.

2.3 Information Capacity of Poisson (Optical) Channels

The determination of the channel capacity, under fixed energy constraints, of a poisson (optical) channel evolves as a deceptively complicated problem. A poisson channel is one in which a transmitted intensity x is converted to y photo electrons, where the conditional density of y given x is poisson with intensity parameter x. Various approximations in the past have been invoked to give approximate capacity formulas, and even upper and lower bounds can

generally be established. However, determination of the probability density in x that achieves the capacity involves the solution of fairly complicated equations. Such a result would be important since it would define the optical field that achieves maximum information rate. It is known [7] that the entropy of the channel (photo-detector) output is maximized when y has a Bose-Einstein density, which implies a Rayleigh distributed radiation intensity corresponding to a Gaussian field. However, the results for channel capacity (entropy-equivocation) are not so easily determined. The use of calculus of variations appear to indicate that the Bose-Einstein density is not the solution for maximum capacity.

The addition of additive poisson noise (e.g. background radiation) appears as an even more complicated problem. It is hoped that results can be obtained for this case also. In previous works [7] the assumption of additive gaussian white noise lead to the conclusion that the capacity was approximately one half the entropy of the source. This result is somewhat suspect.

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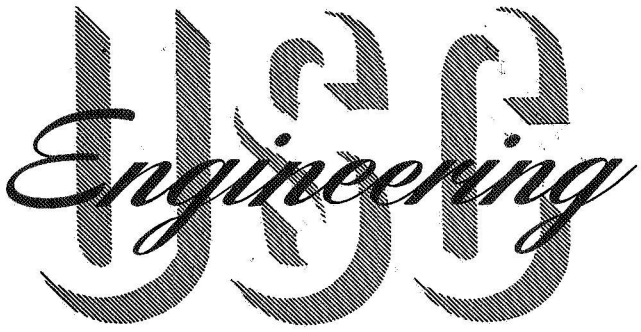
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