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Foreward

The research sponsored under this award deals with investigations of possible improvements that may be made in direct detection optical communication systems through the use of arrays of semiconductor laser diodes. One such improvement consists of the use of a new modulation format, termed color coded optical pulse position modulation (CCPPM). The transmitter consists of an array of N individual laser diodes, each temperature tuned to a separate laser wave-length that does not overlap in frequency the laser light produced by any of the other diodes in the array. The details of this communication system are described in the following paper.

Direct-Detection Optical Communication with Color Coded Pulse Position Modulation Signaling†

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ABSTRACT

The performance of a direct-detection optical communication system in which the laser transmitter sends short optical pulses of selected nonoverlapping center frequencies is analysed. This modulation format, in which a single light pulse is sent in one of M time slots at one of N optical center frequencies, is referred to as color coded optical pulse position modulation (CCPPM). The optimum energy-efficiency of this system, as measured by the channel capacity in nats per photon, exceeds that of ordinary optical pulse position modulation which uses a pulsed laser of fixed optical frequency. It is also shown that reliable communication at optimal energy efficiency can easily be achieved through the use of modest block length Reed-Solomon codes with the code words represented as CCPPM symbols.

I. Introduction

Recent advances in Gallium-Arsenide (GaAs) semiconductor laser technology [1]-[4] have produced renewed interest in free-space satellite-to-satellite optical communication links. One proposed system is based on a precisely controlled c-w GaAs diode laser and heterodyne detection [5]. Direct detection systems have also been proposed that use various forms of direct intensity modulation of the semiconductor laser [6]. While both types of systems have their own particular advantages as well as disadvantages, it is generally thought direct detection systems are simpler and less expensive to implement.

An attractive modulation format for direct detection systems is the pulse position modulation (PPM) signaling scheme proposed by Pierce [7]. In this format, a single light pulse of $\Delta\tau$ seconds duration and fixed optical center frequency is transmitted in one of Q time slots. If the input to the communication system consists of equally likely binary digits, Q is restricted to an integer power of two. It is well known that the capacity of this Q-ary optical PPM channel is given by [7]

$$C = (1-e^{-\lambda_s \Delta\tau}) \log_2 Q \text{ bits/symbol} \tag{1}$$

under free-space propagation and no background light conditons. Here $\lambda_s \Delta\tau$ is the mean number of photons received per time slot and $\exp(-\lambda_s \Delta\tau)$ is the probability the received PPM symbol is lost due to erasure (i.e. no photons received in any of the Q time slots). The channel throughput (average number of correctly received bits/symbol) is given by

$$C_T = (1-e^{-\lambda_s \Delta\tau}) \frac{\log_2 Q}{Q\Delta\tau} \quad \text{bits/sec} \tag{2}$$

In order to make most efficient use of the transmitter output energy, the channel capacity per photon, given by

$$C_{ph} = (1-e^{-\lambda_s \Delta\tau}) \frac{\log_2 Q}{\lambda_s \Delta\tau} \quad \text{bits/photon} \tag{3}$$

should be maximized, subject to the constraints C_T=constant and $\Delta\tau$ (which is a measure of detector bandwidth needed) fixed.

In the work that follows, it will be shown that the energy efficiency, as measured by C_{ph}, of this direct detection PPM optical communication system can be substantially increased if the transmitter can be made to produce short duration light pulses with an optical center frequency that can be selected as one of N unique, nonoverlapping frequencies. This can be accomplished by either a single tunable semiconductor laser diode, or by an array of N individual diodes, each temperature tuned to a single unique fixed center frequency. Fortunately, the technology of tunable GaAs laser diodes is rapidly developing [2], [3], and such lasers may soon become available.

The color coded optical PPM (CCPPM) communication system discussed here consists of the following. A group of L successive binary source digits is encoded as one of NM total possible color coded PPM symbols. The code symbol will be transmitted as a light pulse not more than $\Delta\tau$ seconds in duration in one of M possible time slots at one of N possible optical center frequencies. The light pulses will be directly detected through the use of a diffraction grating and an array of photodetectors. The grating and associated optics are used to focus a light pulse of a particular center frequency onto only one of the photodetectors in the array. The N different optical frequencies have to be spaced far enough apart so that the diffraction patterns produced by the grating and optics do not overlap at the plane containing the detector array. The output of each detector in the array is then examined in each of the M time slots to determine if any photons were detected. In the absence of background radiation and for ideal photodetectors, only one detector will receive any light, and the light it receives will be contained entirely in only one time slot. It is assumed that there are negligibly small differences in optical path lengths from the grating to each element of the detector array.

The analysis of this communication channel, presented in the next section, will reveal that its energy efficiency, as measured by C_{ph}, can substantially exceed that of a single optical frequency PPM system. This increased energy efficiency incurs two penalties however. The first is that N separate photodetectors are required, as opposed to only one for ordinary PPM. In a sense, information encoded as the optical frequency part of the code symbol is decoded by purely passive optical components of relatively high efficiency into spatial information (i.e. position) in the detector array. The second penalty is that the increase in channel capacity in bits/photon is achieved through a decrease in the number of received photons per time slot. This means the code symbol erasure probability has been increased. As a result, the increased erasure probability must be compensated for through the use of additional coding. Reed-Solomon codes have been shown to be a good choice to accomplish this for the optical PPM channel [8], and section III illustrates how they may be used in the context of this CCPPM system to achieve reliable communication.

In the following discussions, it is convenient to express the quantities given by (1)-(3) in units of nats rather than bits. In all cases this simply involves replacement of $\log_2$ with the natural logrithm, denoted by $\ln$.

Lesh et al. [9] have shown that for the noiseless optical PPM communication channel, the channel capacity is limited to 2 nats/symbol, even if $\Delta\tau$ is allowed to become arbitrarily short (i.e. the detector has infinite bandwidth). A similar phenomenon is observed here in that as the number of frequencies N is allowed to increase and $\Delta\tau$ is held fixed, the capacity of the color-coded PPM system never exceeds 2 nats/symbol.

II. Capacity of the Color Coded Optical PPM Channel

The communication system will transmit a group of L binary source digits encoded as one of the NM possible CCPPM symbols once every T seconds. The possible output symbols from the receiver consist of the NM input symbols, and an erasure symbol. The erasure symbol is detected when no photons at all are absorbed by any of the N photodetectors in the array.

In order to compute the channel capacity, the transition probabilities between output symbols and input symbols must be known. These are essentially the same as for ordinary PPM. Consequently,

$$C = (1-e^{-\lambda_s \Delta\tau})\,\ln(NM) \qquad \text{nats/symbol} \tag{6}$$

This reduces to (3) for $N = 1$, the channel capacity of the PPM system using fixed frequency laser light. However, $\Delta\tau$ and T are related here as $M = T/\Delta\tau$ rather than $Q = T/\Delta\tau$.

The throughput, C_T, of this system is given by

$$C_T = (1-e^{-\lambda_s \Delta\tau}) \frac{\ln(NM)}{M\Delta\tau} \quad \text{nats/second} \tag{7}$$

since one CCPPM symbol is transmitted every $M\Delta\tau$ seconds. If the system is to be used to transmit a block of L binary source digits every T seconds, it is clearly desirable to have $Q_{TOT} = 2^L$. The rate at which the binary source digits can be transmitted is then $\ln(NM)/(\ln 2)M\Delta\tau$ binary source digits per second. Since $1-\exp(-\lambda_s\Delta\tau)$ is the probability the received CCPPM symbol is correctly detected (i.e. not erased), the average number of source digits per second that are correctly received with this system is given by $C_T/\ln 2$.

In order to make most efficient use of the laser output pulse energy, the capacity per photon, C_{ph}, should be as large as possible. For the CCPPM system, C_{ph} is given by

$$C_{ph} = (1-e^{-\lambda_s \Delta\tau}) \frac{\ln(NM)}{\lambda_s\Delta\tau} \quad \text{nats/photon} \tag{8}$$

The capacity in nats/photon for ordinary PPM is given by (8) with $N = 1$. Since the binary source data rate is simply related to C_T, it is useful to express C_{ph} in terms of C_T, N, M and $\Delta\tau$ with the aid of (7) as

$$C_{ph} = -\frac{C_T M\Delta\tau}{\ln[1 - C_T M\Delta\tau/\ln(NM)]} \quad \text{nats/symbol} \tag{9}$$

The behavior of (9) with $N = 1$ was studied in [9] and [10] as a function of $C_T, \Delta\tau$, and M. For fixed $C_T\Delta\tau$, C_{ph} was found to have a single maximum determined by the PPM alphabet size, M. Furthermore, reference [10] gave a proof that $C_T M \Delta\tau \leq 2$ nats/photon for any choice of $C_T\Delta\tau$. Both [9] and [10] show that the maximum value of C_{ph} increases as $\Delta\tau$ decreases for fixed C_T, and also as C_T decreases for fixed $\Delta\tau$. Since the binary source rate the communication system should transmit will determine C_T, $\Delta\tau$ should be as short as possible. At present $\Delta\tau$ is limited by the bandwidth of available photodetectors to about 10^{-9} seconds. The laser light pulse can be shorter than this (in fact 10^{-12} - 10^{-13} second laser light pulses can be generated) without deterioration of the system performance, provided no background radiation or intrinsic detector noise sources are present.

The behavior of (9) for the CCPPM communication format was investigated as a function of N and M for a fixed value of $\Delta\tau = 10^{-9}$ seconds with C_T as a parameter by direct computer numerical evaluation. Note that from (8), $\lambda_s\Delta\tau$, the mean number of received photons per time slot, must be greater than zero, and is given by

$$\lambda_s\Delta\tau = -\ell n[1-C_T M\Delta\tau/\ell n(NM)] \qquad (10)$$

Consequently, $0 \leq C_T M\Delta\tau/\ell n(NM) < 1$. The variation of (9) with M, the number of time slots, is shown in Figure 1 for $C_T = 10^4$ and 10^8 nats/second, and two values of N. The choice $N = 1$ corresponds to ordinary PPM and duplicates the results of [9]. $N = 100$ corresponds to CCPPM with 100 different, nonoverlapping laser wavelengths. The optimal value of C_{ph}

in nats/photon has been increased due to the use of the CCPPM signaling system. The curves have a single maximum and "nosedive to zero" due to the rapid increase in $\lambda_s\Delta\tau$, the denominator of (9) as $C_T M\Delta\tau/\ell n(NM)$ approaches unity. Equations (9) and (10) are undefined if $N \cdot M = 1$, or more generally, if $C_T M\Delta\tau/\ell n(NM) > 1$.

The value of the number of time slots which renders C_{ph} a maximum is denoted by M^*. Figure 2 gives the dependence of M^* with N. The value of M^* changes very slowly with N due to the extremely slow growth of $\ell n(NM)$. Values of M^* for $N = 1$ and $N = 10^6$ are indicated on the Figure. Note that, since $\Delta\tau = 10^{-9}$ seconds, all cases studied yielded $C_T M^* \Delta\tau \leq 2$. Since C is given by $C_T M\Delta\tau$, values of the CCPPM alphabet size, $Q_T = NM$, that make most efficient use of laser transmitter energy apparently yield a communication system characterized by a channel capacity of not more than 2 nats/symbol.

The dependence of the optimal channel capacity, C^*_{ph}, in nats/photon on the number of colors used in the code (i.e. N) is shown in Figure 3, for a range of values of throughput, C_T. C^*_{ph} is observed to increase monotonically for values of $C_T \leq 10^8$ nats/second. At $C_T = 5 \times 10^8$, N must exceed 2, and $M^* = 3$ for $2 \leq N \leq 30$. M^* increases to 4 for values of N between 30 and 10^6. At $C_T = 10^9$, $C_T\Delta\tau = 1$ and C^*_{ph} is undefined for $N < 4$, since $C_T M\Delta\tau/\ell n(NM)$ exceeds unity for all values of M. In the range $4 \leq N \leq 6$, $M^* = 1$. Above $N = 6$, M^* remains constant at 2. For values of C_T in excess of 10^9 nats/second, C^*_{ph} remains undefined for an ever larger range of values of N, and all M. Once N becomes sufficiently large that $C_T\Delta\tau/\ell n(N) \leq 1$, M^* remains unity and C^*_{ph} is as shown in Figure 3 for $C_T = 5 \times 10^9$ and 1×10^{10}

nats/second. In this regime, however, the modulation format has become one of pure color coding, as there is only one time slot. Since the transmitter laser has to be fired once every $M\Delta\tau$ seconds, operation in this regime implies the existence of an internal frequency selection device that can set the laser oscillation frequency to some desired value in a time short compared to $\Delta\tau$ (here taken as 10^{-9} seconds). The alternative is to use an array of N laser diodes, each tuned to a unique frequency as the transmitter. Further discussion will be restricted to cases where $C_T \leq 5 \times 10^8$ nats/symbol.

As mentioned in the introduction, the increase in C^*_{ph} with N results from the decrease in the value of $\lambda_s\Delta\tau$ which renders C_{ph} a maximum. Figure 4 plots the mean number of photons per slot, $\lambda_s\Delta\tau$, given by (10) with M set equal to M^*, versus N. C_{ph} is defined only for integer values of N and M, although smooth curves have been drawn in the figures. The bumps in the curves are small M effects, and are only noticable on logrithmic scales at high values of C_T where M is small and changes by unity at certain points as N increases. As can be seen from Figure 4, $\lambda_s\Delta\tau$ decreases rapidly with N at high values of C_T, but only very slowly with N at low values of the throughput.

The increased energy efficiency results from the decrease of the mean number of photons per symbol, and not from an increase in the information carried by each CCPPM symbol. As a result, the erasure probability also increases with N. Figure 5 gives the variation of the probability of correct detection, P_D, of the CCPPM symbols as a function of N. At high throughput rates, the probability of correct detection decreases rapidly with N. At low throughput rates, P_D, which is already small, decreases only slightly with N.

The results of the analysis of the performance of the CCPPM system, presented in Figures 2-5, were obtained under the restriction that the throughput, C_T , was held constant. The average number of correctly received binary source digits per second, R_s , output by the system receiver is given by

$$R_s = \frac{(1-\varepsilon)\,\ell n(NM^*)}{M^*\Delta\tau} \quad \text{nats/sec} \qquad (11)$$

where the erasure probability, $\exp(-\lambda_s\Delta\tau)$, has been denoted as ε . Since C_T , given by (7) is constant, both ordinary PPM and CCPPM give the same value of R_s and there is no advantage in using a tunable as opposed to a fixed frequency laser transmitter from this point of view. The advantage of the CCPPM system is clearly revealed if the average laser output power needed to obtain a given R_s is computed as a function of N , subject to M chosen such that C_{ph} is a maximum. Since the transmitter laser has to be fired once every $M^*\Delta\tau$ seconds, and $\lambda_s^*\Delta\tau$ photons per slot have to be received, the average received laser power $\overline{P}_0$, given by $\lambda_s^*\Delta\tau/M^*\Delta\tau$ can be expressed as

$$\overline{P}_0 = -\ell n\left[1-\frac{C_T M^*\Delta\tau}{\ell n(NM^*)}\right]/M^*\Delta\tau \quad \text{photons/sec} \qquad (12)$$

with the aid of (10). The behavior of $\overline{P}_0$ as a function of N with C_T as a parameter is shown in Figure 6. At a throughput of 1×10^8 nats/second, a fixed frequency laser has to be run at an average power level such that 5.38×10^8 photons/second are received by the detector. A tunable laser capable of producing 10^3 nonoverlapping frequencies need be run at an average power level 4.8 times lower, so that 1.12×10^7 photons/second are received by the detectors. The improvement factors are less pronounced at lower throughputs, but are more than a few percent. At $C_T = 10^2$ nats/second, the average received power level of a fixed frequency laser should be 6.75 photons/sec, whereas the tunable, 10^3 CCPPM system needs to produce only 4.40 photons/second at the receiver. The improvement in average power levels required is due to the increase in M^* with N, as shown in Figure 2. The quantity $M/\ln(NM)$ increases monotonically with M for $M \geq 3$, but decreases with N. The net result is the decrease in $\bar{P}_0$ with N for fixed C_T.

III. Reliable Communication

The increase in energy efficiency of the CCPPM system which was accompanied by an increase in erasure probability can be further exploited if some method of correcting for the erasures without increasing the transmitted power levels is used. It has been pointed out in [8] and [11], that first encoding the binary source digits as code words of a Reed-Solomon (RS) code, and then using a PPM format to represent the individual RS code symbols can yield a substantial improvement in system performance. The same is true here. Each CCPPM symbol will represent one code word of an (n,k) RS code, where n is the length of the block of RS code words to be transmitted and k is the number of information bearing symbols in the block. In this idealized situation, the only source of error is symbol erasure. The RS code can correct for all patterns of $n-k$ or fewer erasures. The block length n is constrained to be 2^L-1, where L

is the number of binary source digits transmitted by each information bearing symbol in the block. Consequently $n+1 = 2^L = NM$, the number of CCPPM symbols to be used. First consider k restricted to be approximately $n/2$ since McEliece [8] has found that the smallest block error probability, P_e, for a given bandwidth after coding for the optical PPM channel is obtained for RS codes of dimensionless rate $k/n \simeq 1/2$. The block error probability, P_e, is given by

$$P_e = \sum_{s=n-k+1}^{n} \binom{n}{s} \varepsilon^s (1-\varepsilon)^{n-s} \tag{13}$$

where ε is the symbol erasure probability. The bit error probability is approximately $\frac{1}{4} P_e$ under these conditions [11]. A plot of P_e versus the erasure probability, ε, for (31,16), (63,32), (127,64), (255,128), (511,256) and (1023, 512) RS codes reveals that once the symbol erasure probability approaches and exceeds 0.5, reliable communication cannot be achieved regardless of block length. This is because these RS codes can correct for at most erasures of one half the code symbols in the block. Figure 5 indicates that CCPPM signaling under conditions where C_{ph} is a maximum yields erasure probabilities substantially larger than 0.5 under all conditions except at values of throughput, C_T, greater than 10^8.

Reliable communication under conditions of maximum energy efficiency can be obtained by sending fewer information bearing symbols per RS code block, i.e. by reducing k. The binary input source data rate, R_S, can be expressed as

$$R_s = \frac{k}{n}\frac{N}{\Delta\tau}\;\frac{\ell n(NM^*)}{NM^*} \quad \text{nats/sec} \tag{12}$$

where $NM^* = n+1$. Furthermore, let us interpret reliable communication to mean the block error probability, (13), does not exceed approximately 10^{-8} . Once the code block length n and erasure probability ε are specified, this requirement then determines k through (13).

Figure 7 shows the behavior of k as a function of ε for RS (31,k), (63,k), (127,k) and (255,k) codes over the appropriate regions of interest. The improvement in source data rate that can be obtained with CCPPM signaling under conditions of both reliable communication and maximum energy efficiency can be demonstrated from Figure 7 with the use of Figure 5.

First consider the case $C_T = 10^8$ nats/symbol. M^* , from Figures 2 and 5 is 17 or 18, but will be taken as 16 since NM must be an integer power of two. From Figure 5, ordinary PPM (N=1) requires an RS (15,k) code with erasure probability $\varepsilon^*=0.42$ to operate at maximum energy efficiency. Since $(0.42)^{15}$ exceeds 10^{-8} , reliable communication cannot be achieved under these conditions. At two level CCPPM signaling (M=16, N=2), the erasure probability is 0.52 . From Figure 5, an RS (31,1) code yields $Pe \leq 10^{-8}$ at a source data rate, from (12), of 7×10^6 nats/second. C_{ph} generally changes very slowly with M for fixed N , and the use of $M=16$, rather than the optimal value $M^*=17$, results in an almost imperceptable decrease in energy efficiency (2.5837 nats/photon as opposed to the optimal value of 2.5838 nats/photon with $M^*=17$, N=2) . As the level of color coding increases, so does the source data rate that can be reliably transmitted. At N=4 , M=16, an RS (63,6) code with symbol erasure probability $\varepsilon^*=0.59$ will reliably convey information at a source data rate of 24.7×10^6 nats/sec, at an energy efficiency of 3.29 nats/photon . At N=8, M=16, an RS (127,18) code with erasure probability $\varepsilon = 0.64$ achieves a source data rate of 43×10^6 nats/sec at an efficiency of 4 nats/photon. Finally a 16 color level, 16 time slot transmitter can convey information reliably at an energy efficiency of 4.70 nats/photon at a source data rate of 58×10^6 nats/sec if an RS (255,43) code is used at a symbol erasure probability of 0.68 . The improved error correction capability of the RS codes with increasing block length apparently far outweighs the slow increase in symbol erasure probability due to operation of the color coded system at maximum energy efficiency.

The same behavior is true at both higher and lower throughput rates, with the energy efficiency increasing as the throughput decreases. At $C_T = 5 \times 10^8$ nats/sec , $M^* = 4$, for $N > 30$. A 32 color level, four time slot system has an optimal erasure probability of $\varepsilon^* = 0.58$. An RS (127,25) code yields reliable communication at a source data rate of 239×10^6 nats/sec and efficiency of 3.76 nats/photon. At $N = 64$, $M^* = 4$, $\varepsilon^* = 0.64$, an RS (255,52) code results in reliable communication at a source data rate of 283×10^6 nats/sec at an efficiency of 4.47 nats/photon .

At $C_T = 10^7$ nats/second , $M^* = 182$, which is an awkward value. Ordinary PPM with 128 time slots requires an RS (127,9) code and yields a source data rate of 2.68×10^6 nats/sec at an efficiency of 4.18 nats/photon. The optimal value of C_{ph} is 4.23 nats/photon with

$M^* = 182$. Two level CCPPM requires an RS (255,25) code, and has $R_s = 4.24 \times 10^6$ nats/sec at an efficiency of 4.88 nats/photon.

At lower values of throughput, M^* is so large that extremely long block length RS codes would be required, and it is at present not technologically feasible to implement them.

IV. Summary

The use of a laser transmitter that can produce short duration light pulses at selected optical center frequencies has been shown to produce a performance advantage over that of a similar, fixed frequency laser in a direct detection optical communication system based on a pulse position modulation format. At equal throughputs, the energy efficiency of the CCPPM system exceeds that of the ordinary (fixed laser frequency) PPM system in direct proportion to the logarithm of the number of non-overlapping optical frequencies the tunable transmitter laser can produce. Even though the increase in energy efficiency results in a larger symbol erasure probability than the ordinary PPM system, reliable communication can still be achieved through the use of modest block length Reed-Solomon codes. In the case of CCPPM signaling, as the RS code block length increases, so does the binary source data rate the system can reliably transmit, with both system throughput and detector bandwidth remaining fixed. This occurs because the CCPPM alphabet size (which is determined by the RS code block length) can be increased by increasing the number of nonoverlapping optical frequencies used in the code, without the necessity of increasing the number of time slots used.

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List of Figure Captions

Figure 1. Channel capacity in nats per photon as a function of number of time slots, M, for ordinary (N=1) and 100 level color coded PPM signaling for two values of channel throughput.

Figure 2. Number of time slots, M^*, versus number of colors, N, used in CCPPM signaling such that C_{ph} is a maximum under conditions of fixed detector bandwidth, $\Delta\tau^{-1}$, and channel throughput, C_T.

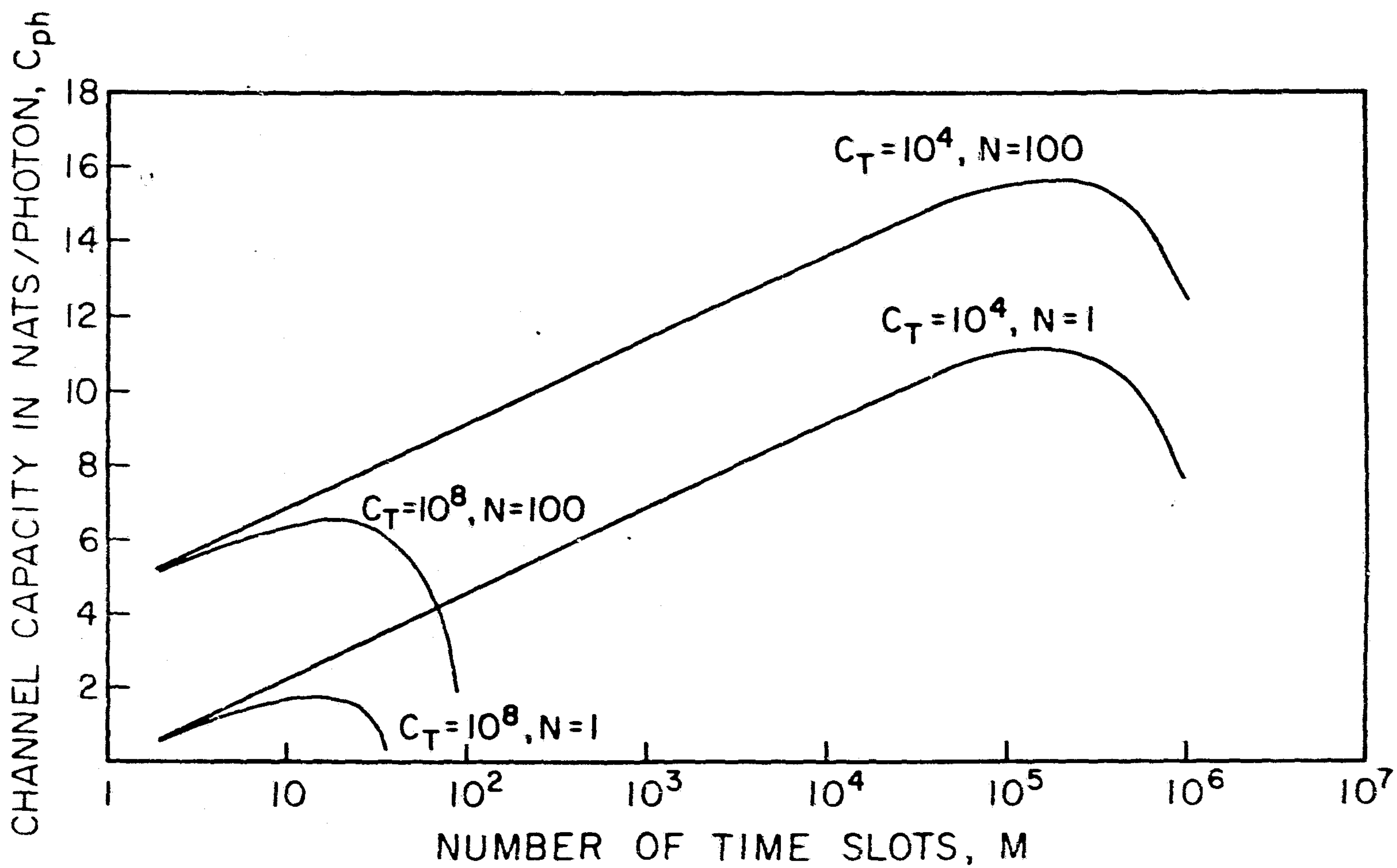
Figure 3. Optional energy efficiency in nats per photon versus number of colors used in CCPPM signaling at various values of channel throughput C_T.

Figure 4. Average number of received photons in each time slot, $\lambda_s \Delta\tau$, as a function of the number of colors used in CCPPM signaling under conditions of maximum energy efficiency for various values of channel throughput, C_T. M^* values for $C_T \leq 10^8$ can be obtained from Figure 2.

Figure 5. Probability of correct detection of the CCPPM symbols as a function of the number of colors used in CCPPM signaling under conditions of optimal energy efficiency for various values of channel throughput, C_T.

Figure 6. Average received laser power in units of photons (i.e. photodetector counts) per second as a function of the number of colors used in CCPPM signaling under conditions of maximum energy efficiency for various values of channel throughput, C_T.

Figure 7. Number of information bearing symbols in an (n,k) RS code as a function of code symbol erasure probability, ε, such that the block error probability does not exceed approximately 10^{-8}.



CHANNEL CAPACITY IN NATS/PHOTON, C_{ph}
18
16
14
12
10
8
6
4
2
1
10
10^2
10^3
10^4
10^5
10^6
10^7
NUMBER OF TIME SLOTS, M
$C_T=10^4$, N=100
$C_T=10^4$, N=1
$C_T=10^8$, N=100
$C_T=10^8$, N=1

Figure 1.

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OF POOR QUALITY

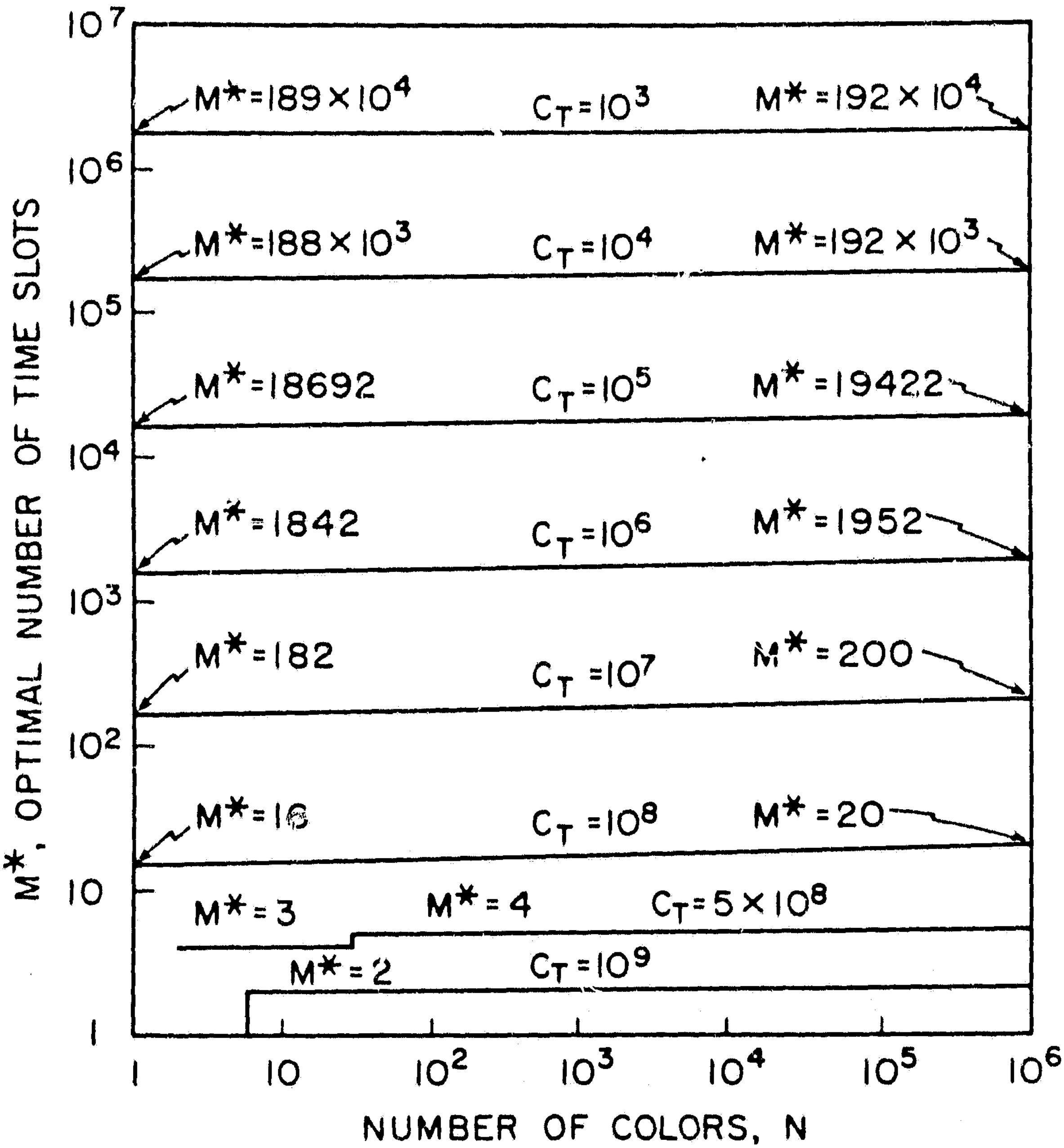

Figure 2.

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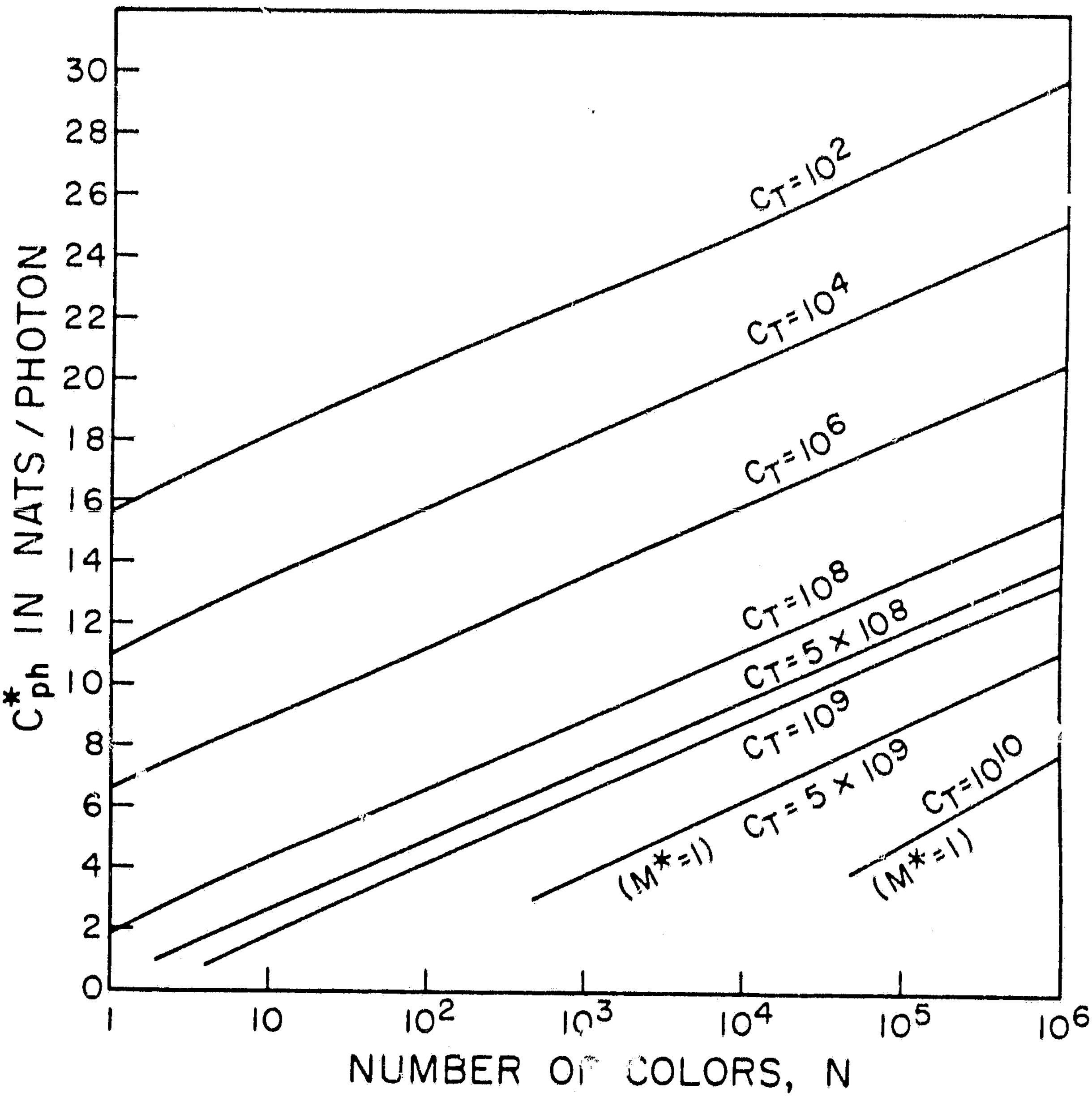
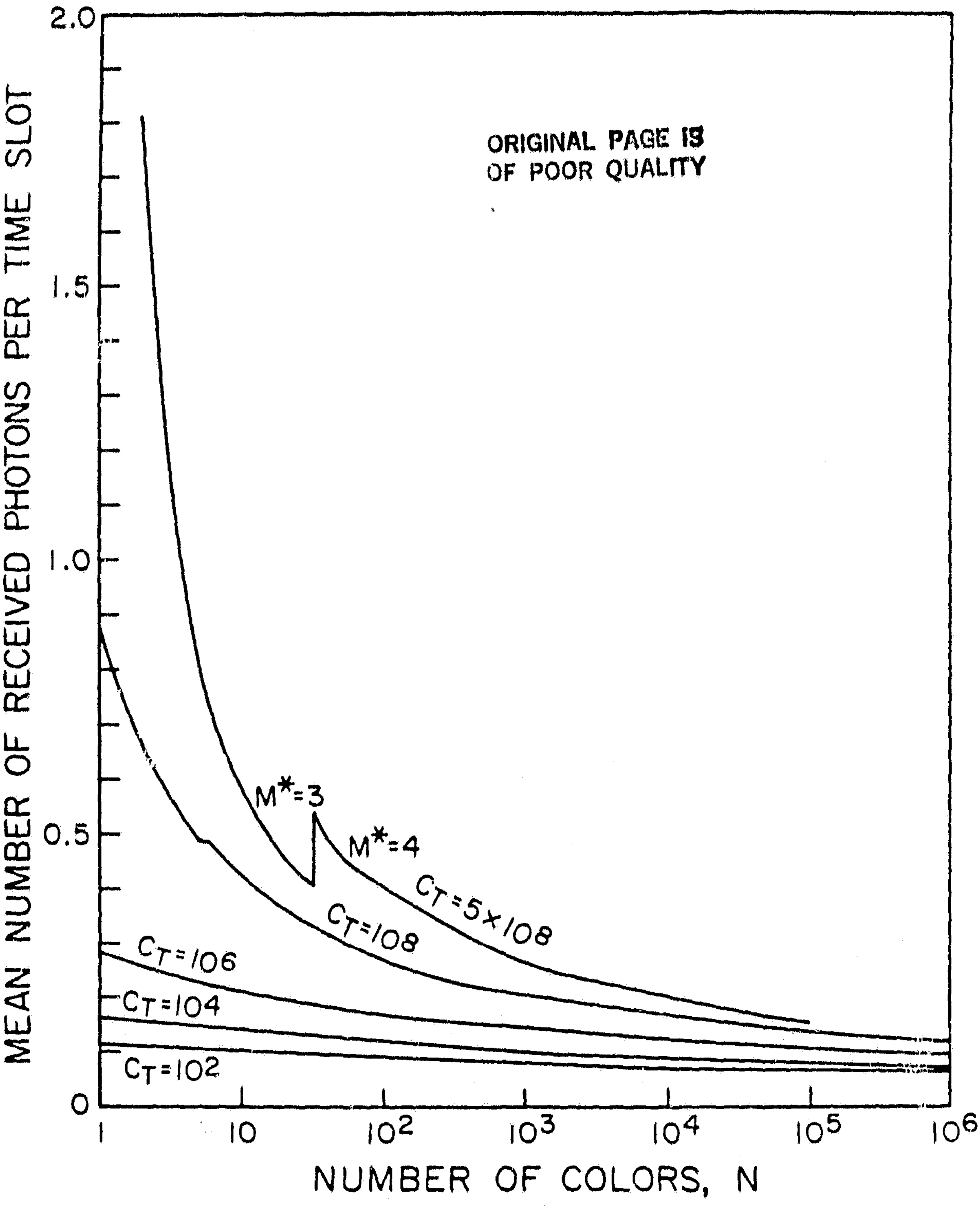


Figure 3.



MEAN NUMBER OF RECEIVED PHOTONS PER TIME SLOT
NUMBER OF COLORS, N
2.0
1.5
1.0
0.5
0
1
10
10^2
10^3
10^4
10^5
10^6
ORIGINAL PAGE IS
OF POOR QUALITY
M*=3
M*=4
C_T=5×10^8
C_T=10^8
C_T=10^6
C_T=10^4
C_T=10^2

Figure 4.

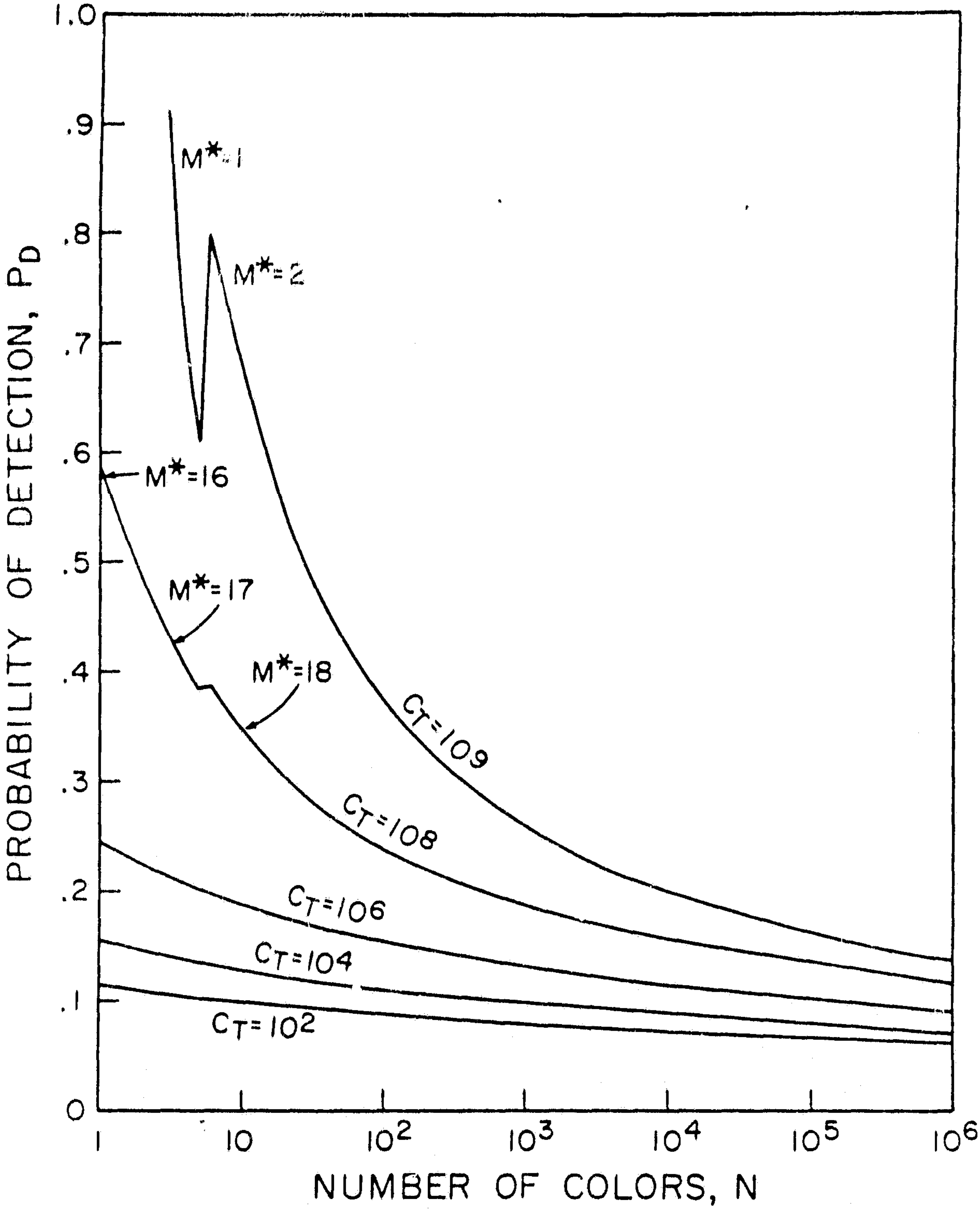

1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
PROBABILITY OF DETECTION, P_D
M*=1
M*=2
M*=16
M*=17
M*=18
C_T=109
C_T=108
C_T=106
C_T=104
C_T=102
1
10
10^2
10^3
10^4
10^5
10^6
NUMBER OF COLORS, N

Figure 5.

ORIGINAL PAGE IS
OF POOR QUALITY

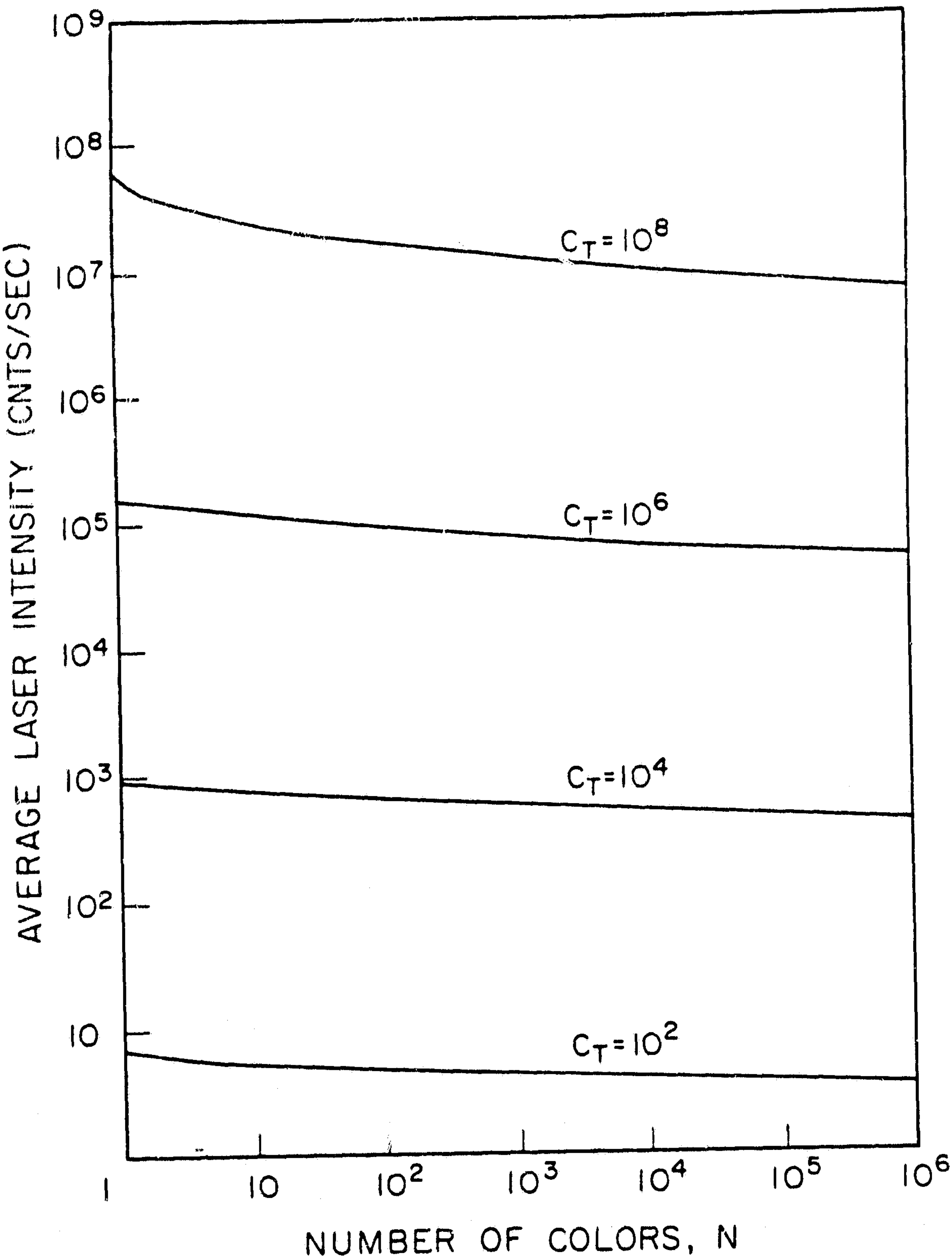


Figure 6.

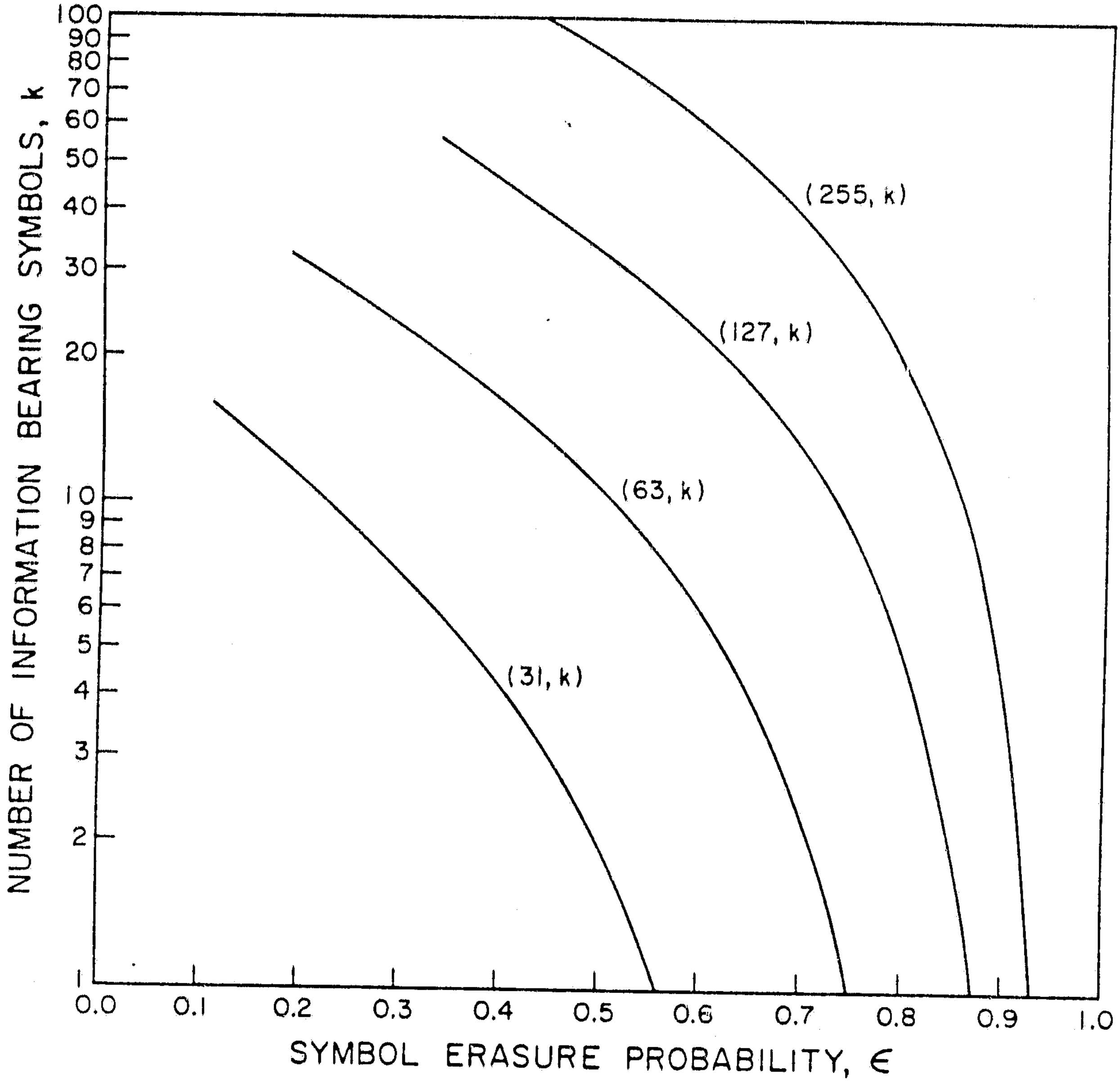

NUMBER OF INFORMATION BEARING SYMBOLS, k
SYMBOL ERASURE PROBABILITY, ϵ
(255, k)
(127, k)
(63, k)
(31, k)
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

Figure 7.