Optimum Threshold Detection in Real-Time Scalable High-Speed Multi-Wavelength Optical Code-Division Multiple-Access LANs

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***Abstract*—We examine the properties and applications of a general class of multi-wavelength optical code-division multiple access codes in high-speed optical local area networks. We demonstrate that *multiple pulse per row codes* with *optimum threshold detection* admit maximization of the number of simultaneous users and spectral efficiency. The code design problem is also greatly simplified when the optimum threshold detection is employed. Based on our results, we propose a simple and low-cost receiver to enable true real-time network optimization.**

***Index Terms*—Correlation receiver, optical code-division multiple access, optical communication networks, optimum threshold detection, real-time scalable networks.**

I. INTRODUCTION

As THE bit rate $\times$ distance product continues to drop and terabit per second systems unstop long-haul bottlenecks, optics is increasingly finding a place in the metropolitan- and local-area network. Several emerging applications are driving the need for high-bandwidth-on-demand in the local-area network environment. Tele-medical imaging requires high-resolution medical images to be transferred uncompressed with low error rate. Distributed supercomputing, video conferencing, and video-on-demand require low-latency access to high-bandwidth transmission [1], [2]. Dense-wavelength-division multiple access (DWDMA) provides abundant bandwidth, but does not currently benefit from low-cost, simple, and decentralized multiple-access methods to allow sharing of a single medium among many users. Complex centralized control and wavelength-tunable laser filters and wavelength converters are often required for wavelength management [22].

Optical code-division multiple access (O-CDMA) systems present an attractive alternative. O-CDMA exploits statistical multiplexing to allow many users to access a shared channel simultaneously without the need for centralized subchannel assignment [3]–[9]. It provides a way of meeting traffic demands in an asynchronous environment at the physical layer. A user may initiate transmission at any time without prior coordination with other users. Latency associated with awaiting the availability of a channel is eliminated.

In earlier proposed systems, the spectrum was spread only in the time domain [3]–[6]. With the advent of cost-effective multi-wavelength optical communication technologies, two-dimensional (2-D) spectral-spreading codes have been developed [7]–[10]. These allow greater exploitation of the fiber bandwidth using modest time-domain chip rates and may, as such, result in cost-effective implementations. The dramatically increased sophistication of functional photonic and optoelectronic integrated circuits which allow combined optical and electronic signal processing via a scalable process [11] makes multi-wavelength O-CDMA (MW-O-CDMA) a natural choice for local area networking.

Recently, much research effort has been devoted to optimizing 2-D MW-O-CDMA codes to support a larger user population. Increasingly effective channel utilization schemes have been proposed [7]–[10]. While the proposed methods are optimized in a static network environment, optimality is not always maintainable in local area networks which have time-dependent and heterogeneous traffic demands. A scheme for true real-time optimization is yet to be developed.

A Gaussian-approximated optimum threshold detection scheme has been proposed by Prucnal *et al.* [12] for synchronous single-wavelength O-CDMA systems operating purely in the time domain. In the present work, we focus instead on multi-wavelength systems in which spectral spreading is carried out in two dimensions. In these systems, the selection of system and code parameters in designing MW-O-CDMA codes can be complicated and computationally intensive due the interdependencies among the many coding degrees of freedom.

We seek to enable true real-time scalability and optimization in MW-O-CDMA networks by a simple change in the receiver design. To this end, we propose an optimum threshold detection scheme for asynchronous O-CDMA in multi-wavelength systems. We derive a simple and readily implemented design procedure for selecting system and code parameters. We consider multiple-pulses-per-row (MPR) codes throughout this work, having demonstrated in an earlier work the added code design flexibility of this approach [13].

An overview of the proposed system, a description of MPR codes, and the mathematical foundation of optimum threshold detection scheme are presented in Section II. In Section III, we present the impact and applications of optimum threshold detection on code design and propose a simple modification to

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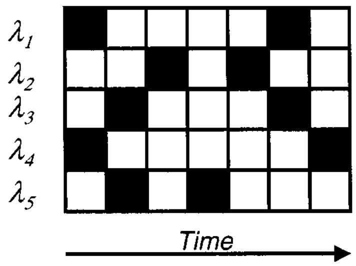


Fig. 1. An example of a MPR code. This figure shows a 5×7 MPR code with ($R =$) 2 pulses per row.

the existing MW-O-CDMA receiver. The detailed derivations of the mathematical models developed herein are presented in Appendixes I and II.

II. MODEL

A. System Description

We assume that N_{su} users transmit simultaneously on the network with no collision. That is, no two users transmit to the same destination—transmitters and receivers are paired up. This requirement must be enforced at the media access control (MAC) level.[1]

Each transmitter/receiver pair is assumed to be chip synchronized. Shot noise and thermal noise are taken to be of negligible power compared to the signal; we focus our attention on the influence of *multiple-access interference*. The effect of shot and thermal noise may be added in cases in which physical noise sources are expected to be of interest [15]. The wavelength channels are assumed to be spaced according to WDM standards (e.g., 100 GHz), and the coherence lengths of low-cost transmitters (e.g., light-emitting diodes and multi-longitudinal mode Fabry–Perot lasers) are much less than node separation. As a result, optical beat noise among adjacent channels is either nonexistent or at least imperceptible at the receivers.

Our work applies to unicast and to multicast transmission. A number of signature patterns can be reserved as multicast groups addresses. In this case, the receivers must be able to decode multiple codes (signature and multicast codes) simultaneously.

B. Multiple-Pulses-per-Row (MPR) Codes

Multiple-pulses-per-row (MPR) codes are a family of 2-D O-CDMA codes which span the time and wavelength domains. Schematically, a MPR code can be represented by a rectangular grid or matrix with N_w wavelength channels (or rows) and L_t time slots (or chips, columns). An example of a 5×7 MPR code is shown in Fig. 1. The black squares represent presence of optical pulses, white squares the absence of a pulse. Fig. 1 illustrates a code which employs two pulses per wavelength channel. MPR codes employ R pulses per row, where R is an integer from 1 to L_t. The requirement of fixed R ensures the uniform distribution of energy (or spread of information) across all wavelength channels. MPR codes with $R > 1$ can be considered as a form of wavelength reuse strategy within a bit period: network resources are better utilized when R is chosen appropriately [13].

MPR codes are versatile—they do no imply a specific code construction algorithm. Our analysis therefore applies to a wide selection of codes. These include the well-known temporal/spatial addition modulo L_t (T/SAML) [9] and wavelength hopping/time spreading (WH/TS) codes [8]. Our analysis is applicable to any 2-D codes—the dimensions in question need not necessarily correspond to wavelength and time.

C. Mathematical Model

Each user is assigned a MPR code matrix (signature pattern) with N_w rows, L_t columns, and a constant weight of $W = N_w R$. L_t is the number of chips per bit, also known as the time-spreading factor. N_w is the number of wavelength channels. R is the number of pulses per wavelength channel in the code matrix.

In previous works [7]–[10] the threshold value used in a correlation receiver was set equal to the code weight. Due to the nonnegativity of the optical channel, optical power can be superimposed, but not cancelled. As a result, setting the threshold value to the code weight ensures no decision error will be made when a bit “1” is sent. This scheme works well when the multiple access interference—the product of the number of simultaneous users with the expectation value of their cross-correlation with the signal to be received—is small compared to the code weight. The probability of error associated with a data bit “0” increases when the average interference power in the optical channel is high. This can be remedied by increasing the threshold value beyond the code weight. It is thus of interest to consider a more general choice of threshold value α, by considering the following expression for the bit error rate (BER):

$$\mathrm{BER} = \frac{1}{2}\left[\begin{array}{l}\displaystyle\sum_{i=0}^{\alpha-1-N_wR}\binom{Nsu-1}{i}\left(\frac{N_wR^2}{2L_t}\right)^i\left(1-\frac{N_wR^2}{2L_t}\right)^{N_{su}-1-i}\\ \displaystyle+\sum_{i=\alpha}^{N_{su}-1}\binom{Nsu-1}{i}\left(\frac{N_wR^2}{2L_t}\right)^i\left(1-\frac{N_wR^2}{2L_t}\right)^{N_{su}-1-i}\end{array}\right]. \quad (1)$$

We plot in Fig. 2 the BER as a function of the threshold value. It is seen that the BER is minimized at a threshold value greater than the code weight. The results indicate that, when multiple access interference is high, a substantial improvement in error performance can be achieved by treating the threshold value as a free parameter to be chosen optimally.

The optimum threshold value α_{opt} which minimizes the total probability of error is given by

$$\alpha_{\mathrm{opt}} = \frac{N_wR}{2}\left(\frac{N_{su}\cdot R}{L_t}+1\right). \quad (2)$$

Equations (1) and (2) are derived in Appendix I.

Treated as a continuous parameter, the optimum threshold value need no longer an integer as was the case when it was set equal to the code weight.

[1]A scheme similar to the CSMA media access rule deployed in Ethernet [14] can be used where transmitters serialize their transmission to the same recipient by listening to the channel for the recipient code pattern. If the recipient code pattern is present on the channel, the transmitter waits for a random period of time before making another attempt to transmit.

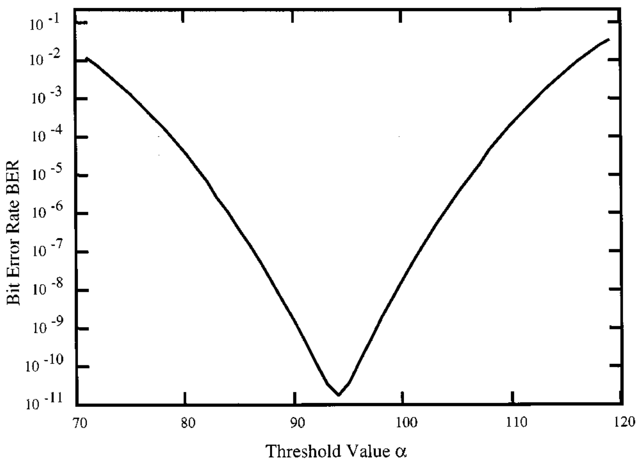


Fig. 2. Existence of optimum threshold value. The BER of a MPR code with a total spreading factor S of 5000 and a weight of 70 supporting 120 users is minimized by choosing a threshold value of 94.

III. Results

A. Code Design

The selection of code and system parameters in MW-O-CDMA codes is a difficult multivariable problem in view of the interdependencies among parameters in (1). The design process is often iterative and involves intensive numerical computation which is time-consuming and may fail to provide intuitive insight into the generalized code design problem.

We find in this section that not only is system performance greatly improved, but the code design problem is also greatly simplified, if the system employs optimum threshold detection. We show in Appendix II that when optimum threshold detection is deployed, a Gaussian approximation of the BER expression in (1) may be obtained using the central limit theorem:

$$\mathrm{BER}^{G} = Q\left(\sqrt{\frac{N_{su}N_{w}R^{2}\left(1-\frac{N_{w}R^{2}}{2\cdot L_{t}}\right)}{2\cdot L_{t}}}\right) \tag{3}$$

where the superscript G indicates that (3) is a Gaussian approximation and $Q(\bullet)$ is the well-known *Q-function* [16]. It follows that the complex interdependencies of the code and system parameters are reduced to a set of simple expressions interrelated by the code weight W

$${}^{OT}N_{su} = \frac{W^{2}}{p^{2}} = \frac{S}{p^{2}} \tag{4a}$$

$${}^{OT}L_{t} = N_{w}\cdot R^{2} = W\cdot R \tag{4b}$$

$${}^{OT}S = N_{w}\cdot L_{t} = W^{2} \tag{4c}$$

$$\alpha_{\mathrm{opt}} = \frac{W}{2}\left(\frac{W}{p^{2}}+1\right) \tag{4d}$$

where S is the total spreading factor and p is a function of the BER given by $Q^{-1}(\mathrm{BER})$. For example, if a BER of 10^{-9} is required, the value of p is 5.99 [16]. The superscript OT emphasizes the fact that these expressions are direct consequences of optimum threshold detection.

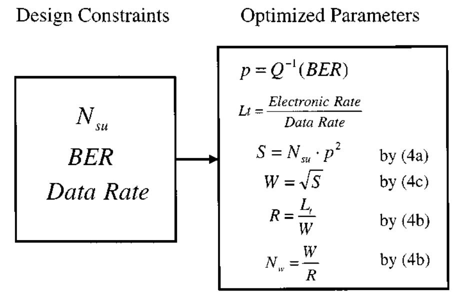


Fig. 3. System and code parameters selection procedure.

If we let B_e be the rate at which chips can be sent using the available hardware, then the temporal spreading factor L_t is tied to the individual user data rate according to

$$\text{User Data Rate} = \frac{\text{Electronic Processing Rate}}{\text{Tempora Spreading Factor}} = \frac{B_2}{L_t}. \tag{5}$$

In a deployment-oriented code design problem where the desired BER, number of simultaneous users, and user data rate are specified, the remaining parameters are given by (4). These dependencies are depicted in Fig. 3.

B. Network Performance

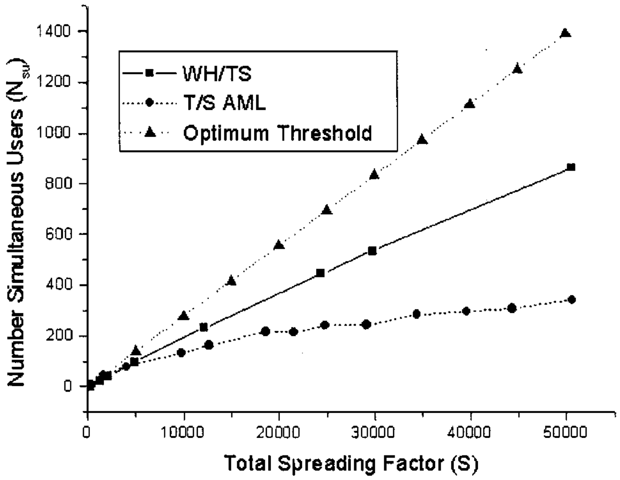
Using the code design algorithm proposed in the previous section, we compare the performance of the WH/TS [9] and T/S AML [8] codes with conventional threshold detection, and MPR codes with optimum threshold detection.

We show in Fig. 4(a) that MPR codes with optimum threshold detection support more users simultaneously at a BER of 10^{-9} than do the WH/TS and T/S AML codes with the same total spreading factor. In Fig. 4(b), we show that the code with optimum threshold detection also sustains a higher constant spectral efficiency than the diminishing spectral efficiency of the WH/TS and T/S AML codes. Optimal threshold detection provides maximum improvement when multiple access interference, and thus the network size, is large. In a network with 150 users and a BER of 10^{-9}, a total spreading factor of 5400 is needed, at which point optimal threshold detection provides approximately 50% higher spectral efficiency.

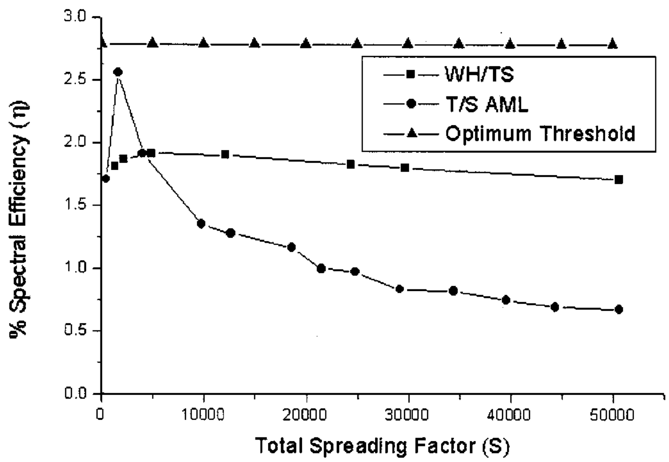
The spectral efficiency of WH/TS and T/S AML follows a highly nonlinear multi-variable relationship, whereas the spectral efficiency of the code with optimum threshold detection is only a function of the BER as derived in Appendix II

$$\eta = p^{-2}. \tag{6}$$

Equation (6) is conceptually consistent with the general information theoretic result that the most efficient use of the multiple-access channel is achieved not by creating many orthogonal or nearly-orthogonal sub-channels, but by having every user superimpose its signal onto the channel and having a decorrelator determine the single hypothesis which could yield the measured superposition of signals [17]. The result points to the value of forward-error correction in allowing a desired error rate to be achieved while drastically improving spectral efficiency [18].



(a)



(b)

Fig. 4. Network performance comparison between WH/TS [8] and T/S AML [9] codes with conventional threshold detection; and MPR codes using optimal threshold detection. In each case a BER of better than 10^{-9} is achieved. (a) Maximum achievable number of simultaneous users. (b) Spectral efficiency.

C. Receiver Design

The deployment of optimum threshold detection allows the network to maintain optimal operation under varying traffic conditions without modification to the code set in use.

It can be seen from (2) that the optimum threshold value depends only on the number of simultaneous users on the network given a particular code set. The number of simultaneous users can be inferred from the total average power—a quantity which increases in proportion with the number of users transmitting simultaneously. To achieve continuous adjustment of the optimum threshold value we consider the receiver design depicted in Fig. 5.

The lower arm of the receiver is a conventional O-CDMA receiver. The noise-like multi-wavelength signal is de-spread by the correlator and the energy of the de-spread pulse is then measured using a photodetector. A binary decision as to the received bit is made based on the pulse energy compared to the threshold level.

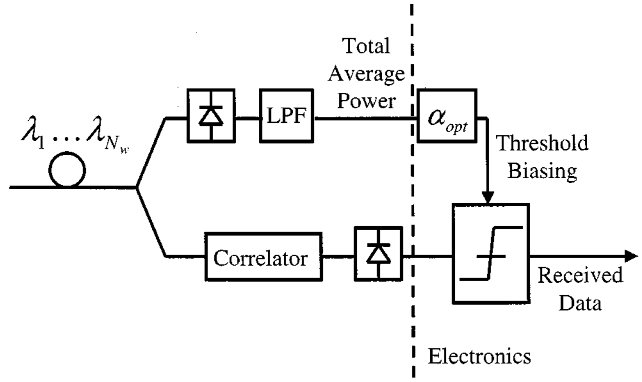


Fig. 5. Receiver design using real-time threshold optimization.

To realize optimum threshold detection, an upper arm is added to the receiver design. A photodetector is used to measure the total optical power summed over all wavelength channels [19]. This signal is then processed by a low-pass filter to eliminate short time-scale fluctuations. The average optical power is used to compute the optimum threshold level to be used by the threshold element.

IV. CONCLUSION

In this work we have developed a computationally efficient design algorithm for multiple-pulse-per-row codes with optimum threshold detection. Our procedure allows instantaneous system and code parameter selection and improved channel utilization. A simple, low-cost correlation receiver design is proposed which allows real-time threshold optimization without changing the code set or the hardware in use. Our approach enables the realization of real-time self-optimizing networks.

The results of this work point to the following avenues for future exploration.

1) Decentralized Media Access Control: With the power monitoring capability described in the Section III-C, a simple decentralized media access control mechanism similar to the *persistent CSMA* media access rule deployed in Ethernet [14] can be implemented in order to prevent congestion in a network in which demand exceeds intrinsic capacity. Further study is needed to tailor this scheme for MW-O-CDMA systems.

2) Fusion of Error Control Codes (ECC) and O-CDMA Codes: ECCs improve the reliability of data transmission through noisy channels by introducing rules into transmitted code words so that the system can recover from transmission errors. With the use of such mechanism, the *absolute* BER requirement on the MW-O-CDMA could be potentially relaxed and further optimized. There are two ways ECCs can be incorporated in our system: 1) encode raw data bits with ECCs before encoding with O-CDMA codes and 2) amalgamate the design of ECC and O-CDMA codes. While the former is simple to implement, the latter yields a higher performance code set potentially. Further study is needed to understand the design tradeoffs and performance gain.

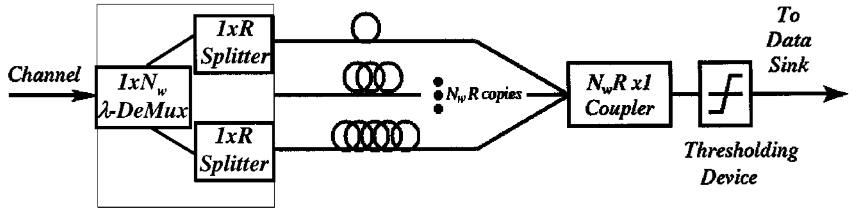


Fig. 6. A conventional receiver design using optical fiber delay line for multi-wavelength MPR codes systems.

APPENDIX I
BIT ERROR RATE AND OPTIMUM THRESHOLD DETECTION ANALYSIS

To obtain the BER for the MPR code, we consider first the superposition of two MPR codes with random time shift. If we limit the cross correlation constraint λ_c to 1, there exist R^2 possible distinct overlapping patterns in any one row. There are a total of $N_w R^2$ overlaps in N_w rows and the probability of overlap is $N_w R^2/2L_t$. We assume each transmitter is equally likely to transmit a data bit 1 or 0 and we let the threshold value of the correlation receiver be α. The probabilities of error when a data bit 1 and 0 are sent are given by

$$P(\text{error}|1) = \sum_{i=0}^{\alpha-1-N_w R} \binom{Nsu-1}{i} \left(\frac{N_w R^2}{2L_t}\right)^i \cdot \left(1 - \frac{N_w R^2}{2L_t}\right)^{N_{su}-1-i} \tag{A.1a}$$

$$P(\text{error}|0) = \sum_{i=\alpha}^{N_{su}-1} \binom{Nsu-1}{i} \left(\frac{N_w R^2}{2L_t}\right)^i \cdot \left(1 - \frac{N_w R^2}{2L_t}\right)^{N_{su}-1-i}. \tag{A.1b}$$

$P(\text{error}|1)$ and $P(\text{error}|0)$ are known as *the probability of false dismissal and the probability of false alarm* respectively [20]. Combining (A.1a) and (A.1b), we obtain the expression for the BER as shown in (A.2) at the bottom of the page. In (A.2), the probability of false dismissal and false alarm correspond to two disjoint regions under the same binomial distribution. These two regions are separated by a distance equal to the code weight $N_w R$ as shown in Fig. 7.

In order to minimize the total probability of error, it is necessary to minimize the sum of the probability of false dismissal and false alarm. This is equivalent to minimizing the total shaded areas under the binomial distribution curve. In the high MAI regime,[2] the binomial distribution approaches the symmetric shape shown in Fig. 7. With all other parameters held constant, varying the threshold value is equivalent to sliding along the horizontal axis a *blank column* with a fixed width equal to the code weight $N_w R$. The goal is to maximize

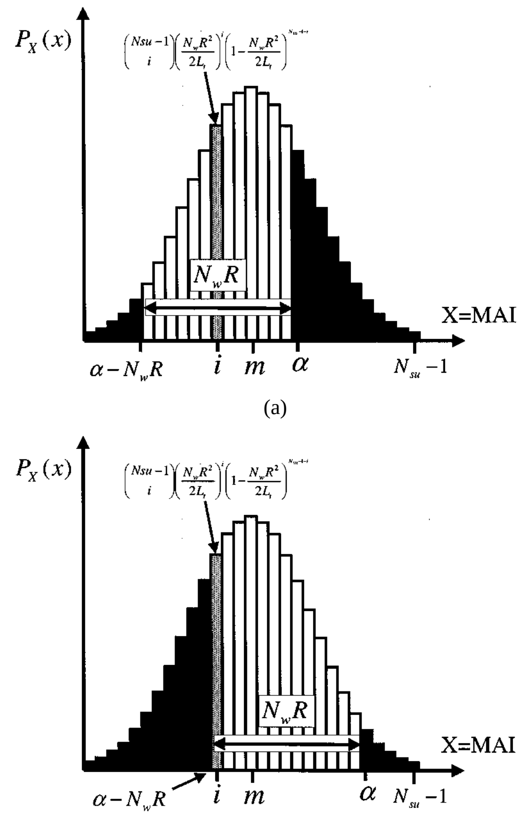


Fig. 7. BER for different choices of threshold values. (a) Probability of false alarm and (b) probability of false dismissal dominates. The BER is given by the total area of the shaded area.

[2]A large user population is generally required to sustain operation in high MAI regime. The number of users required could exceed the cardinality of some codes such as the T/S AML and WH/TS codes. Fortunately, the cardinality of such codes can be dramatically increased by performing cyclic shifts in the wavelength domain [21].

$$\text{BER} = \frac{1}{2}\left[P(\text{error}|1) + P(\text{error}|0)\right] = \frac{1}{2}\left[\begin{array}{l} \displaystyle\sum_{i=0}^{\alpha-1-N_w R} \binom{Nsu-1}{i} \left(\frac{N_w R^2}{2L_t}\right)^i \left(1 - \frac{N_w R^2}{2L_t}\right)^{N_{su}-1-i} \\ \displaystyle+ \sum_{i=\alpha}^{N_{su}-1} \binom{Nsu-1}{i} \left(\frac{N_w R^2}{2L_t}\right)^i \left(1 - \frac{N_w R^2}{2L_t}\right)^{N_{su}-1-i} \end{array}\right] \tag{A.2}$$

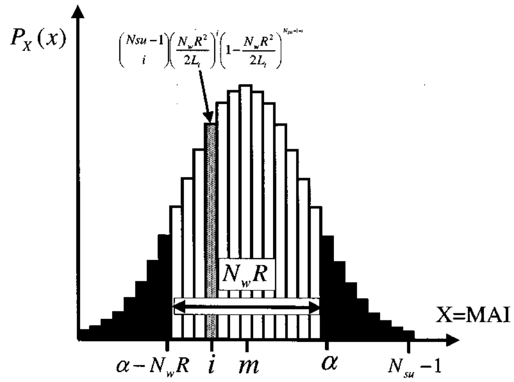


Fig. 8. BER at optimum threshold value. The blank-out area is placed in the center of the binomial distribution to achieve minimized BER. The BER is given by the total area of the shaded area.

the area covered by the fixed width column so that the area covered by the probability of false dismissal and false alarm is minimized. This is achieved by centering the column about the mean of the binomial distribution as shown in Fig. 8.

With the mean of the binomial distribution given by

$$m = (N_{su} - 1)\left(\frac{N_w \cdot R^2}{2L_t}\right) \tag{A.3}$$

the optimum threshold value is then given by:

$$\alpha_{\text{opt}} = m + \frac{N_w R}{2} = \frac{N_w R}{2}\left(\frac{N_{su} \cdot R}{L_t} + 1\right). \tag{A.4}$$

The value of the threshold α should never be set below the code weight $N_w R$. $P(\text{error}|1)$ is identically zero for $\alpha \le N_w R$. Since $P(\text{error}|1)$ remains zero for $\alpha \le N_w R$, whereas $P(\text{error}|0)$ increases, setting the threshold value below the code weight can only increase the total probability of error. The optimum threshold value is

$$\alpha_{\text{opt}} = \begin{cases} m + \dfrac{N_w R}{2} = \dfrac{N_w R}{2}\left(\dfrac{N_{su} \cdot R}{L_t} + 1\right), & \dfrac{N_{su} \cdot R}{L_t} \ge 1 \\ N_w R, & \dfrac{N_{su} \cdot R}{L_t} < 1. \end{cases} \tag{A.5}$$

Appendix II
Optimum Threshold Detection Code Design

The equation for the BER (A.1) can be simplified with the help of the central limit theorem [16]. At optimum threshold, the probability of false dismissal equals the probability of false alarm and the BER becomes

$$\begin{aligned}\text{BER} &= \tfrac{1}{2}\left[P(\text{error}|1) + P(\text{error}|0)\right] \\ &= P(\text{error}|1) \\ &= \sum_{i=\alpha}^{N_{su}-1} \binom{Nsu-1}{i} \left(\frac{N_w R^2}{2L_t}\right)^i \left(1 - \frac{N_w R^2}{2L_t}\right)^{N_{su}-1-i}\end{aligned} \tag{A.5}$$

and the mean and variance of this binomial distribution are given by

$$m = (N_{su} - 1)\left(\frac{N_w \cdot R^2}{2L_t}\right) \tag{A.6a}$$

$$\sigma^2 = (N_{su} - 1)\left(\frac{N_w \cdot R^2}{2L_t}\right)\left(1 - \frac{N_w \cdot R^2}{2L_t}\right). \tag{A.6b}$$

A Gaussian approximation of (A.5) can then be obtained using the central limit theorem when the number of simultaneous users N_{su} is sufficiently large that $N_{su} - 1 \approx N_{su}$

$$\begin{aligned}\text{BER}\big|_{\alpha_{\text{opt}}} &= \frac{1}{\sqrt{2\pi}} \int_{\alpha_{\text{opt}}}^{\infty} e^{-t^2/2}\, dt \\ &= Q\left(\frac{\alpha_{\text{opt}} - m}{\sigma}\right) \\ &= Q\left(\frac{N_w R/2}{\sigma}\right) \\ &= Q\left(\sqrt{\frac{N_w L_t}{2N_{su}\left(\frac{1-N_w e^2}{2L_t}\right)}}\right) \\ &= Q(p)\end{aligned} \tag{A.7}$$

where $Q(\bullet)$ is the well-known Q-*function* [16].

Equating the parameters in the Q-*function* in the last two steps of (A.7) allows solution for the number of simultaneous users

$$N_{su} = \frac{N_w L_t}{2 \cdot p^2 \left(1 - \frac{N_w R^2}{2 \cdot L_t}\right)}. \tag{A.8}$$

This is the number of simultaneous users a network with optimum threshold detection can support while satisfying constraints imposed by other parameters including the BER [given by $Q^{-1}(\text{BER})$] and user data rate (given by B_e/L_t). However, the job of system design is still difficult with (A.8) as all the system parameters are related interdependently. Fortunately, this intricate interdependency can be untangled by setting

$$\left(1 - \frac{N_w R^2}{2 \cdot L_t}\right) = \frac{1}{2}$$

in (A.8). With this observation, the following set of equations is produced:

$${}^{OT}L_t = N_w \cdot R^2 = W \cdot R \tag{A.9a}$$

$${}^{OT}S = N_w \cdot L_t = (N_w \cdot R)^2 = W^2 \tag{A.9b}$$

$${}^{OT}N_{su} = \frac{W^2}{p^2} = \frac{S}{p^2} \tag{A.9c}$$

$$\alpha_{\text{opt}} = \frac{W}{2}\left(\frac{N_{su} \cdot W}{S} + 1\right) = \frac{W}{2}\left(\frac{W}{p^2} + 1\right) \tag{A.9d}$$

where W is the code weight equals to $N_w R$. Equation (A.9) reduces the complex interdependencies of the system and code parameters into a set of simple relationships. In a deployment-oriented network design problem, each parameter can be completely specified with the knowledge of BER, number of simultaneous users, and user data rate as illustrated in Fig. 3.

Spectral efficiency, which we define as the ratio of information rate to total bandwidth consumed, can be obtained from (A.9)

$$\eta = \frac{\text{Total Information Rate}}{\text{Total Bandwidth}} = \frac{N_{su}}{N_w \cdot L_t} = \frac{1}{p^2}. \quad \text{(A.10)}$$

The spectral efficiency of MPR codes with optimum threshold is constant once the desired BER is specified.

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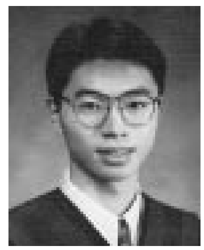

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