CO-CHANNEL INTERFERENCE CANCELLATION IN OPTICAL SYNCHRONOUS CDMA COMMUNICATION SYSTEMS

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Abstract - Three co-channel interference cancellation techniques are proposed for synchronous optical CDMA communication systems. Modified prime sequence optical codes that exhibit a grouping characteristic are employed. In the first technique the desired user collects primary decisions from receivers of all interfering users and subtracts them, after properly weighting, from its received signal. In the second and third techniques the desired user collects photodetector outputs from users in its same group and subtracts them from its received signal after a proper scaling.

I. INTRODUCTION

CDMA effectively utilizes the wide bandwidth of optical communication medium [1-5]. Synchronous [1-3] and asynchronous [4-5] CDMA have been considered in the literature. It is known [2] that a synchronous CDMA system accommodates a larger number of users and the available number of spreading codes is larger since the same code can be reused with different phases. The maximum number of users in a CDMA system is limited by the maximum tolerable interference, termed as co-channel interference. This noise-like interference is in fact not completely random. If the receiver is able to cancel it, the system performance can be improved.

This paper proposes three interference cancellation techniques for optical synchronous CDMA. We select the *modified prime sequence codes* developed in [2] to demonstrate the techniques. The first technique is general while the second and third techniques are more tailored for the modified prime sequence codes. The analysis considers a direct-detection optical channels utilizing number-state light field. The background noise is assumed negligible. The paper is organized as follows. The synchronous CDMA system is described and analyzed in section II without interference cancellation. Sections III, IV and V are devoted for the description and analysis of the three cancellation techniques, respectively. Numerical results are given in section VI. Finally the findings and conclusions are given in section VII.

II. OPTICAL SYNCHRONOUS CDMA

The synchronous CDMA system considered in this paper is similar to that in [2]. It employs *modified prime sequence* optical PN codes. Given a prime number p, p^2 codes of period p^2 are generated. The p^2 codes are grouped in p groups with p codes in each group. Therefor code j belongs to group $\lfloor (j-1)/p \rfloor + 1$, where $\lfloor a \rfloor$ is the integer part of *a*. The cross-correlation function between two chip synchronous codes $a_i(m)$ and $a_j(m)$ of length p^2 is given by:

$$C_{i,j}(n) = \sum_{m=0}^{p^2-1} a_j(n+m)\, a_i(m), \tag{1}$$

where n is the phase shift between the two codes. For a synchronous system n=0. Denoting $C_{i,j}(0)$ by $C_{i,j}$, the modified prime sequence codes given in [2] have:

$$C_{i,j} = \begin{cases} p\ ; & i=j \\ 0\ ; & i \text{ and } j \text{ are from same group and } i \neq j \\ 1\ ; & i \text{ and } j \text{ are from different groups} \end{cases}, \tag{2}$$

which signifies that at the sampling instant users in the same group will have zero mutual interference while any two users from different groups will have the same mutual interference with unity cross-correlation. Each user in the system is permanently assigned a unique code as its signature. There are N users, $N \le p^2$. Codes are assigned to users randomly, with a uniform distribution. Throughout the paper when referring to user j then reference is also made to code j and the user is considered in the group that includes code j. A binary on-off keying scheme is used where each user transmits its signature sequence if its data bit is 1 and ceases transmission otherwise. All transmitters use the same power so that all signals are received with the same power. The data bits of user j $\{b_j\}$ are modeled as independent random variables (r.v.'s) that take the values of 1 or 0 with equal probability. Define the r.v. γ_j, $j \in \{1,2,\ldots p^2\}$ as

$$\gamma_j = \begin{cases} 1\ ; & \text{if code } j \text{ is assigned to a user} \\ 0\ ; & \text{if code } j \text{ is not assigned to a user} \end{cases}. \tag{3}$$

Therefore $\sum_{j=1}^{p^2} \gamma_j = N$. Without loss of generality for the remainder of this paper we assume that code 1 is assigned to user 1 ($\gamma_1=1$) and we evaluate the probability of bit error for user 1. We assume that any receiver knows all the current users, the used codes and their respective groups. The receiver of user 1 correlates the compound received sequence of laser pulses with its address code. The correlator consists of tapped delay lines as explained in [1]. Hence, the correlator photon count of user 1 is proportional to (we will always assume a unity factor of proportionality):

$$\begin{aligned} Z_1 &= pb_1 + \sum_{j=2}^{p^2} b_j C_{1,j} \gamma_j = pb_1 + \sum_{j=p+1}^{p^2} b_j \gamma_j \\ &\equiv pb_1 + Y \end{aligned}, \tag{4}$$

where the interference Y is equal to the total number of users sending "1" in groups 2,3,...., and, p. Let the r.v. T represent the number of users in the first group. The probability density function (pdf) of Y, conditioned on T, is therefore given by:

$$\Pr(Y=y|T=t) = \frac{1}{2^{N-t}} \binom{N-t}{y}, \quad y \in \{0,1,\ldots,N-t\}. \tag{5}$$

The receiver of user 1 decides $b_1=1$ if $Z_1 \ge \theta$ and $b_1=0$ if $Z_1 < \theta$. The optimum value of θ depends on N and T. Since $b_1=0$ or 1 with equal probability, and due to the symmetrical shape of the binomial pdf (7) around its mean, the optimum value of θ is half way between the statistical means of $Z_1|b_1=0$ and $Z_1|b_1=1$, giving $\theta = (N+p-T)/2$ and the probability of error, conditioned on T, is given by

$$\Pr(E|T=t)=\frac{1}{2}\left[\Pr(Y\ge\theta|T=t)+\Pr(Y<\theta-p|T=t)\right].^*$$

This probability is different for integer or non-integer θ. Using (7) it can be shown that if θ is an integer the probability of error is given by

$$\Pr(E|T=t)=\frac{1}{2^{N-t}}\left\{\sum_{y=0}^{r}\binom{N-t}{y}-\frac{1}{2}\binom{N-t}{r}\right\}, \tag{6,a}$$

while if θ is a non-integer the probability of error is given by:

$$\Pr(E|T=t)=\frac{1}{2^{N-t}}\sum_{y=0}^{\lfloor r\rfloor}\binom{N-t}{y}, \tag{6,b}$$

where r is given by $r=(N-p-t)/2$. If p>N-t r<0 and (6,a) and (6,b) yield a zero probability of error. Since the minimum value of t is 1, error free transmission occurs for N<p+1.

The probability of error is given by averaging (6) over the pdf of T. Given that user 1 always exists, and with uniform distribution of the N-1 other users over the other p^2-1 codes in the system, the pdf of T is found as:

$$\Pr(T=t)=\frac{\binom{p^2-p}{N-t}\binom{p-1}{t-1}}{\binom{p^2-1}{N-1}},\quad t\in\{t_{\min},\ldots,t_{\max}\} \tag{7}$$

where $t_{\min}=\max\{1,N-p(p-1)\}$ and $t_{\max}=\min\{N,p\}$, where max{*a*,*b*} and min{*a*,*b*} are the maximum and minimum of *a* and *b*, respectively. The optimum probability of error is evaluated from (6) and (7).

III. FIRST TYPE OF CANCELLATION (CANCELLER 1)

Canceller 1 is shown in figure 1. All receivers make a primary decision on whether the transmitted signal is "1" or "0" by comparing the output of the photodetector to a threshold. This threshold depends on N and the number of users in the group and is the same for users in the same group. Define T_i, X_i, Y_i and θ_i to be the number of users, the number of users sending "1", the interference that a receiver gets, and the threshold employed in decision, respectively, for group i. However, since reference to group 1 is very frequent in this paper, in future sections we denote T_1, X_1, Y_1 and θ_1 by T, X, Y and θ, respectively. Clearly there are T_i-X_i users in group i sending "0" and N is equal to the sum of all T_i's.

Receiver 1 multiplies the primary decision of user j, for all j≠1, by the cross-correlation C_{1j} of (2) and adds up all the results. The total is subtracted from Z_1 of (5) to form a new decision variable $\tilde{Z}_1$. Equation (2) leads to the implementation shown in figure 1. $\tilde{Z}_1$ is compared to another threshold α and "1" is declared to be sent if $\tilde{Z}_1\ge\alpha$, otherwise "0" is declared.

We first find the pdfs of T_i and X_i. {T_i} are dependent r.v.'s while, conditioned on all T_i, {X_i} are independent. The pdf of T_1 is given by (7). In a similar manner the pdf $p(T_i|T_{i-1},T_{i-2},\ldots,T_1)$ for i=2,3,...,p is given by:

$$\Pr(T_i=t_i|T_{i-1}=t_{i-1},T_{i-2}=t_{i-2},\ldots,T_1=t_1)=\frac{\binom{p(p-i)}{N-\sum_{j=1}^{i}t_j}\binom{p}{t_i}}{\binom{p(p-i+1)}{N-\sum_{j=1}^{i-1}t_j}}\quad t_i\in(t_{i,\min},t_{i,\max}) \tag{8}$$

where $t_{i,\min}=\max\left\{0,N-p(p-i)-\sum_{j=1}^{i-1}t_j\right\}$,

and $t_{i,\max}=\min\left\{p,N-\sum_{j=1}^{i-1}t_j\right\}$. The pdf's of {$X_i$}, conditioned on {$T_i$}, i=1,2,...,p, are given by the binomial distributions, for i=1:

$$\Pr(X_1=x_1|T_1=t_1,b_1=0)=\left(\frac{1}{2}\right)^{t_1-1}\binom{t_1-1}{x_1}, \tag{9,a}$$

where in (9,a) x_1=0,1,...t_1-1

$$\Pr(X_1=x_1|T_1=t_1,b_1=1)=\left(\frac{1}{2}\right)^{t_1-1}\binom{t_1-1}{x_1-1} \tag{9,b}$$

where in (9,b) x_1=1,2,...t_1

and for 1< i ≤p

$$\Pr(X_i=x_i|T_i=t_i)=\left(\frac{1}{2}\right)^{t_i}\binom{t_i}{x_i},\quad x_i=0,1,\ldots,t_i. \tag{9,c}$$

For users in any group i>1 there are X_i users whose received photon count is p+Y_i, and T_i-X_i users whose received photon count is Y_i., where $Y_i=\sum_{j=1,\,\ne i}^{p}X_j$. To generate the primary decisions, each receiver applies its photon count as the argument of the function $\phi_i(a)=\begin{cases}1 & a\ge\theta_i\\ 0 & a<\theta_i\end{cases}$. The receiver of user 1 builds the new decision r.v.

$$\begin{aligned}\tilde{Z}_1&=Z_1-\left[\sum_{i=2}^{p}X_i\phi_i(p+Y_i)+(T_i-X_i)\phi_i(Y_i)\right]\\&=pb_1+\left\{\sum_{i=2}^{p}X_i\left[1-\phi_i(p+Y_i)+\phi_i(Y_i)\right]-T_i\phi_i(Y_i)\right\}.\\&\equiv pb_1+G_1\end{aligned} \tag{10}$$

To decide on the transmitted bit, $\tilde{Z}_1$ is applied to the function $\varphi(a)=\begin{cases}1 & a\ge\alpha\\ 0 & a<\alpha\end{cases}$. The probability of error is given by

$$P_b=\frac{1}{2}\left[\Pr(E|b_1=0)+\Pr(E|b_1=1)\right] \tag{11}$$

Let the vectors $\overline{T}=(T_1,T_2,\ldots,T_p)$ and $\overline{X}=(X_1,X_2,\ldots,X_p)$. Then

$$\begin{aligned}\Pr(E|b_1=0,\overline{T}=\overline{t},\overline{X}=\overline{x})&=\Pr(\tilde{Z}_1\ge\alpha)\\&=\varphi(G_1)\end{aligned} \tag{12}$$

where (12) derives from the fact that, given $\overline{T}$ and $\overline{X}$, $\tilde{Z}_1$ in (12) is deterministic. Averaging (12) over $\overline{X}$ and then over T_p, T_{p-1}, T_{p-2}, ..., and then T_1 with that order, one can find:

* Throughout the paper many equations include statistical conditioning. It will be included only in the LHS only.

$$\Pr(E|b_1=0)=\frac{1}{2^{N-1}}\sum_{t_1=t_{1,min}}^{t_{1,max}}\sum_{t_2=t_{2,min}}^{t_{2,max}}\cdots\cdots\sum_{t_p=t_{p,min}}^{t_{p,max}}$$
$$\bullet\sum_{x_1=0}^{t_1-1}\sum_{x_2=0}^{t_2}\cdots\cdots\sum_{x_p=0}^{t_p} A_1A_2\ldots A_p\ B_1B_2\ldots B_p\varphi(G_1) \tag{13}$$

where G_1 is defined in (10) and

$$A_1=\binom{t_1-1}{x_1-b_1},\quad A_i=\binom{t_i}{x_i},\ i>1 \tag{14,a}$$

$$B_1=\frac{\binom{p^2-p}{N-t_1}\binom{p-1}{t_1-1}}{\binom{p^2-1}{N-1}}\ and\ B_i=\frac{\binom{p(p-i)}{N-\sum_{j=1}^{i}t_j}\binom{p}{t_i}}{\binom{p(p-i+1)}{N-\sum_{j=1}^{i-1}t_j}},\ i>1 \tag{14,b}$$

Similarly one can find (note the difference in the limits of x_1)

$$\Pr(E|b_1=1)=\frac{1}{2^{N-1}}\sum_{t_1=t_{1,min}}^{t_{1,max}}\sum_{t_2=t_{2,min}}^{t_{2,max}}\cdots\cdots\sum_{t_p=t_{p,min}}^{t_{p,max}}$$
$$\bullet\sum_{x_1=1}^{t_1}\sum_{x_2=0}^{t_2}\cdots\sum_{x_p=0}^{t_p} A_1A_2\ldots A_p\ B_1B_2\ldots B_p[1-\varphi(p+G_1)] \tag{15}$$

Using (11), (13) and (15) one can find the probability of error for canceller 1. Numerical search for the optimum thresholds θ_i and α is needed. It is found that the combination of any α that satisfies $0<\alpha<1$ and $\theta_i=\lfloor(N+p-t_i)/2\rfloor$ consistently provide an optimum or sufficiently close to optimum performance for all values of N and p.

IV. SECOND TYPE OF CANCELLATION (CANCELLER 2)

From (2), users in the same group get the same interference. The receiver of one user can employ the photodetector output of other receivers in its group to cancel its own interference. A straight forward application is to reserve one code in each group from being assigned to any user. The photodetector output of the correlator of this code consists only of the interference this group gets, which can then be subtracted from all other photodetector outputs. The cost for such system is the loss of p codes, one in each group.

Canceller 2 retains the advantage of error free reception for any group with one or more codes not assigned. It also provides interference cancellation when the codes are assigned to users randomly and when the system is full loaded ($N=p^2$). Figure 2 shows canceller 2 with the constant k=1 in the figure. Considering group 1, the received signal is correlated with *all* codes in the same group, i.e., p correlators are employed even if the number of users in the group < p. User 1 collects photodetector outputs of *all* the p receivers. Similar to (4) these outputs are:

$$Z_j=pb_j\gamma_j+Y\quad j\in\{1,2,\ldots,p\}. \tag{16}$$

The first receiver forms a new decision variable $\tilde{Z}_1$:

$$\begin{aligned}\tilde{Z}_1&=(p-1)Z_1-\sum_{j=2}^{p}Z_j\\&=(p-1)(pb_1+Y)-(p-1)Y-(X-b_1)p\\&=p^2b_1-pX\end{aligned} \tag{17}$$

The pdf of X is given by (9,a and 9,b). The receiver declares that "1" is sent if $\tilde{Z}_1>\theta$ and "0" otherwise. The optimum value of θ is half way between the statistical means of $\tilde{Z}_1|b_1=0$ and $\tilde{Z}_1|b_1=1$, which is $\theta=\frac{1}{2}(p^2-pT)$. By a simple sketch of the pdf's of $\tilde{Z}_1|b_1=0$ and $\tilde{Z}_1|b_1=1$ one can find that the probability of error vanishes if $T<p$ (the two pdf's do not overlap). Therefor error occurs only if $T=p$ and the optimum threshold $\theta=0$, independent of both the number of users in the group and the total number of users. $\tilde{Z}_1|b_1=0$ is always ≤ 0 since $X\ge 0$ and hence the probability of error is zero for $b_1=0$. For $b_1=1$ we have $\Pr(E|b_1=1,T=t)=\Pr(X\ge p)$, and from (9,b) we get

$$\Pr(E|b_1=1,T=t)=\begin{cases}0 & if\ \ t<p\\ \frac{1}{2^{p-1}} & if\ \ t=p\end{cases} \tag{18}$$

As noted above, (18) signifies that if any group has a code not assigned to a user the remaining users in this group enjoy error free reception. The average probability of error is then given from (7) and (18) as

$$P_b=\begin{cases}0\,; & if\ \ N<p\\ \frac{1}{2^p}\frac{\binom{p^2-p}{N-p}}{\binom{p^2-1}{N-1}}\,; & if\ \ N\ge p\end{cases} \tag{19}$$

V. THIRD TYPE OF CANCELLATION (CANCELLER 3)

In canceller 2 the interference term Y in (16) is completely removed and another interference X arises. Canceller 3, on the other hand, removes Y only partially. Canceller 3 is shown in figure 2 with some constant $1>k>0$. Instead of (17) canceller 3 forms the decision variable $\tilde{Z}_1$ as:

$$\begin{aligned}\tilde{Z}_1&=(p-1)Z_1-k\sum_{j=2}^{p}Z_j\\&=p(p-1)b_1-kp(X-b_1)+(p-1)(1-k)Y\end{aligned} \tag{20}$$

Receiver 1 declares that "1" is sent if $\tilde{Z}_1>\theta$ and declares "0" otherwise. From (20) since X and Y have the independent binomial distributions (9,a and 9,b) and (5), respectively, it can be shown that the optimum threshold for group 1 is given by $\theta=[(N-T+p)(p-1)(1-k)+kp(p-T)]/2$. We have

$$\begin{aligned}&\Pr(E|b_1=0,T=t)=\Pr(\tilde{Z}_1>\theta)\\&=\Pr\left(Y>\frac{kp}{(p-1)(1-k)}X+\frac{\theta}{(p-1)(1-k)}\right)\end{aligned} \tag{21}$$

and

$$\begin{aligned}&\Pr(E|b_1=1,T=t)=\Pr(\tilde{Z}_1\le\theta)\\&=\Pr\left(Y\le\frac{kp}{(p-1)(1-k)}(X-1)-\frac{p}{1-k}+\frac{\theta}{(p-1)(1-k)}\right)\end{aligned} \tag{22}$$

The value of k is selected to be $k=\frac{p^2}{1+p^2}$ and it is readily shown that it provides the optimum performance. However, there could be other values that provide optimum performance as well. From (20) the pdf of $\tilde{Z}_1|b_1 = 0$ exists only over the interval {-kp(T-1),(p-1)(1-k)(N-T)}. Also the pdf of $\tilde{Z}_1|b_1 = 1$ exists only over the interval {p(p-1)-kp(T-1),p(p-1)+(p-1)(1-k)(N-T)}. Errors can exist only if these two pdf's overlap. After substituting with the value of k we find that error free transmission occurs if:

$$(p-1)(N-T) < p(p-1)(1+p^2) - p^3(T-1) \tag{23}$$

At this point two cases arise:

Case 1: T<p

Maximizing the LHS of (23) by letting N-T to be N-1 and p-1 to be p and also minimizing the RHS by letting T to be p-1, the condition (23) becomes $N<p^2+p$. Hence, for T<p canceller 3 provides error free transmission. Hence, canceller 3 retains the advantage of error free reception for any group with a code not being assigned to a user.

Case 2: T=p

From (23) error free transmission occurs if N<2p. For (21) we have

$$\Pr(E|b_1 = 0, T = p) = \Pr\left(Y > \frac{kp}{(p-1)(1-k)} X + \frac{N}{2}\right) \tag{24}$$

averaging (24) over X, using (9,a) we get

$$\Pr(E|b_1 = 0, T = p) = \Pr(X = 0)\Pr\left(Y > \frac{N}{2}\right) + \sum_{x=1}^{p-1} \Pr(X = x)\Pr\left(Y > \frac{kp}{(p-1)(1-k)} x + \frac{N}{2}\right) \tag{25}$$

The second term in the RHS of (25) is equal to zero. Applying (9,a) and (7), (25) yields

$$P(E|b_1 = 0, T = p) = \frac{1}{2^{p-1}} \frac{1}{2^{N-p}} \sum_{y > \frac{N}{2}}^{N-p} \binom{N-p}{y} = \frac{1}{2^{N-1}} \sum_{\substack{y=0 \\ \neq \frac{N}{2}-p}}^{\frac{N}{2}-p} \binom{N-p}{y} \tag{26}$$

In a similar manner, from (22)

$$\Pr(E|b_1 = 1, T = p) = \Pr\left(Y \le \frac{kp(X-1)}{(p-1)(1-k)} - \frac{p}{(1-k)} + \frac{N}{2}\right) \tag{27}$$

and averaging over X of (9,b) we get

$$\Pr(E|b_1 = 1, T = p) = \Pr(X = p)\Pr\left(Y \le \frac{N}{2} - p\right) + \sum_{x=1}^{p-1} \Pr(X = x)\Pr\left(Y \le \frac{kp(x-1)}{(p-1)(1-k)} - \frac{p}{(1-k)} + \frac{N}{2}\right) \tag{28}$$

Again the second term in the RHS of (28) vanishes and similar to (26) we get

$$\Pr(E|b_1 = 1, T = p) = \frac{1}{2^{N-1}} \sum_{y=0}^{\lfloor \frac{N}{2}-p \rfloor} \binom{N-p}{y} \tag{29}$$

We recall that the choice of k given earlier is optimum. For T<p this choice yields a zero probability of error. For T=P we note in (25) and (28) that the probability of error is also minimized. Finally from (26) and (29) the probability of error is given by

$$P_b = \begin{cases} \dfrac{1}{2^{N-1}} \dfrac{\binom{p^2-p}{N-p}}{\binom{p^2-1}{N-1}} \displaystyle\sum_{y=0}^{\lfloor \frac{N}{2}-p \rfloor} \binom{N-p}{y} & N \text{ odd} \\ \dfrac{1}{2^{N-1}} \dfrac{\binom{p^2-p}{N-p}}{\binom{p^2-1}{N-1}} \left[\displaystyle\sum_{y=0}^{\frac{N}{2}-p-1} \binom{N-p}{y} + \frac{1}{2}\binom{N-p}{\frac{N}{2}-p} \right] & N \text{ even} \end{cases}$$

VI. NUMERICAL RESULTS AND DISCUSSION

Figures 3 and 4 compare the performance of all systems for p= 5 and 11, respectively. The performance of the non-cancellation system is very poor when the number of users is a multiple of p. Canceller 1 improves the performance when the number of users is low. With larger number of users its performance is even worse than the non-cancellation system. Cancellers 2 and 3, however, provide a significant improvement over both the non-cancellation system and canceller 1 for p=5 and 11. Canceller 3 over-performs all systems for all range of number of users. Figure 5 compares the performance of cancellers 2, 3 and the non-cancellation system for higher values of p. Both cancellers demonstrate a significant improvement that increases rapidly as p increases. Canceller 3 offers a consistent improvement over canceller 2 for the range of p and N shown. Figure 6 shows the performance in case of full load, i.e., $N=p^2$. Again both cancellers offer a significant improvement over the non-cancellation system Canceller 3 continues to over-perform canceller 2 at this high load.

VII. CONCLUSION

Three interference cancellation techniques have been proposed for synchronous optical CDMA systems. In the first, the desired user collects primary decisions form all interfering users and subtracts them from its signal. In the second and third, the desired user collects all other photodetector outputs in its same group and subtracts them from a scaled version of its received signal. The average probability of error is evaluated and the results are compared. A significant improvement of the cancellation techniques over the system without cancellation. Canceller 1 is effective when the number of users is low. Cancellers 2 and 3 provide a significant improvement. Canceller 3 over-performs canceller 2.

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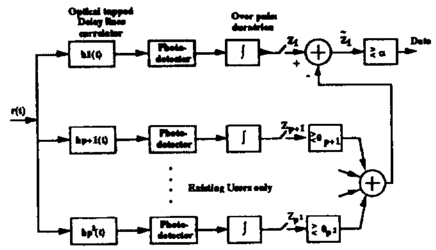

Figure 1, Optical CDMA System with Canceller 1

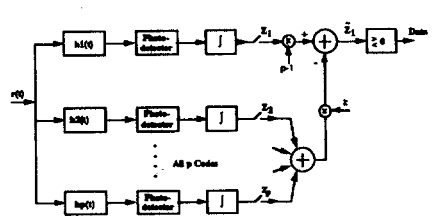

Figure 2, Optical CDMA System with Canceller 2 and Canceller 3

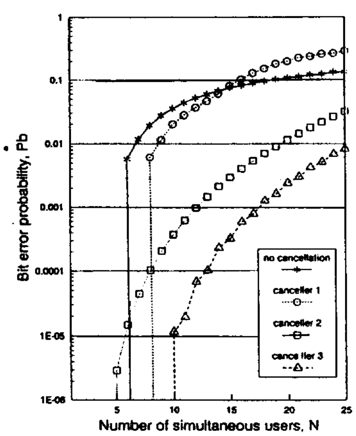

Figure 3, Probability of error versus the number of users with p=5

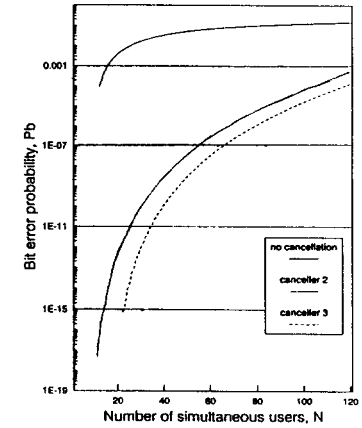

Figure 4, Probabilty of error versus the number of users with p=11

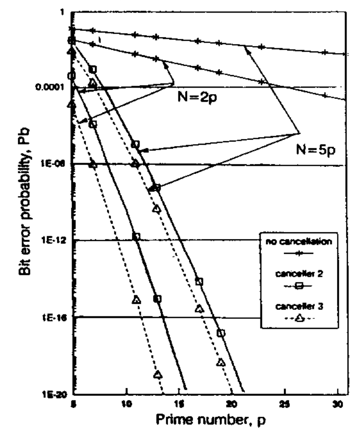

Figure 5, Probability of error versus the prime number with N=2p, N=5p.

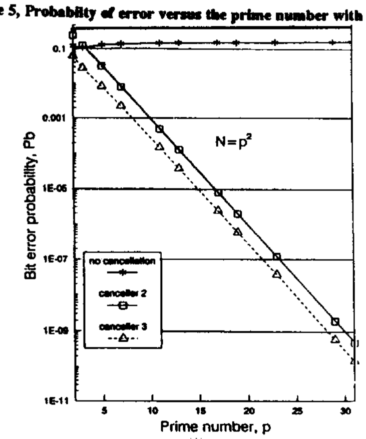

Figure 6, Probability of error versus the prime number with $N=p^2$