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System Performance Comparison of Turbo and Trellis Coded Optical CDMA Systems

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Abstract**—**In this paper, we have compared the performance of a Turbo and Trellis coded optical code division multiple access (OCDMA) system. The comparison of the two codes has been accomplished by employing optical orthogonal codes (OOCs). The Bit Error Rate (BER) performances have been compared by varying the code weights of address codes employed by the system. We have considered the effects of optical multiple access interference (OMAI), thermal noise and avalanche photodiode (APD) detector noise. Analysis has been carried out for the system with and without double optical hard limiter (DHL). From the simulation results it is observed that a better and distinct comparison can be drawn between the performance of Trellis and Turbo coded systems, at lower code weights of optical orthogonal codes for a fixed number of users. The BER performance of the Turbo coded system is found to be better than the Trellis coded system for all code weights that have been considered for the simulation. Nevertheless, the Trellis coded OCDMA system is found to be better than the uncoded OCDMA system. Trellis coded OCDMA can be used in systems where decoding time has to be kept low, bandwidth is limited and high reliability is not a crucial factor as in local area networks. Also the system hardware is less complex in comparison to the Turbo coded system. Trellis coded OCDMA system can be used without significant modification of the existing chipsets. Turbo-coded OCDMA can however be employed in systems where high reliability is needed and bandwidth is not a limiting factor.

Keywords**—**avalanche photodiode, optical code division multiple access, optical multiple access interference, Trellis coded modulation, Turbo code

I. INTRODUCTION

RECENTLY, all optical CDMA techniques have received a growing interest. Optical CDMA (OCDMA) allows multiple users to access the network asynchronously and simultaneously. From the practical view point the OCDMA network is gaining popularity, since it requires minimal optical signal processing and is virtually delay free. In OCDMA systems, the BER performance is degraded by the OMAI, which comes from all the other active users. This in turn ultimately limits the number of active users in a given OCDMA network. In principle, the weight (w) of an OCDMA address code can be increased to reduce the BER for a fixed number of active users in an OCDMA system using an optical orthogonal code (OOC)[1][2][3]. But use of larger code weights results in higher power losses in an OCDMA system. Moreover, using a larger weight causes higher system cost, because more optical delay lines are employed in the OCDMA system and optical 1 × w splitter/w × 1 combiner of a higher weight are required.

To reduce the effect of OMAI, thermal noise and APD detector noise error-correction codes can be used in OCDMA systems. This will permit a choice of lower weight for OCDMA address codes thus reducing the complexity and power loss of the OCDMA encoder/decoder. As will be explained later, an error correction code is used before OCDMA encoding is done at each transmitter and after OCDMA decoding is performed at each receiver. A well-known result from information theory is that randomly chosen code of sufficiently large block length ‘n’ (or the constraint length in case of convolutional codes) is capable of approaching channel capacity. Berrou introduced a new class of error correcting codes called “Turbo codes” which offer a substantial coding gain [4]. They are parallel-concatenated convolutional codes (PCCC) whose encoder is formed by two (or more) constituent systematic convolutional encoders joined through a pseudo-random interleaver. Due to the use of pseudo-random interleaver, turbo codes appear random to the channel, yet posses enough structure so that decoding can be physically realized. The decoding is not maximum likelihood (ML) decoding, but tries to approach ML decoding in an iterative way. For the turbo decoding, MAP (maximum a posteriori) is known to be an optimal choice. There are many sub optimal algorithms such as SOVA (soft output Viterbi algorithm) and Max-log-MAP, which are less complex than the MAP algorithm. In Trellis coded modulation, coding and modulation are combined together [5]. Redundancy is introduced by using more signal points in the constellation than is required for the modulation format of interest with the same data rate [6]. Convolutional coding is used to introduce a certain dependency between successive signal points. Soft-decision decoding is performed at the receiver, in which the permissible sequence of signals is modeled as a trellis structure.

II. SYSTEM MODEL

Multiple accessing is achieved by having multiple sources, each with its own code sequence (called address code), and superimposing their transmissions over a common channel. At

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the receiver end of the OCDMA system, the optical pulse sequence is compared to a stored replica of itself (correlation process). The correlated value is then compared with a threshold level for data recovery. In an incoherent OCDMA network using optical processing, the data messages at the active transmitters using an on-off key are first encoded with their desired OCDMA address code words and are then distributed to each receiver.

In the Turbo/Trellis-coded OCDMA system, information from each user is first encoded into a turbo/ trellis code by a turbo/ trellis encoder, which is further, encoded with the desired OCDMA address code at respective transmitters and then distributed to each receiver. At the receiver side, an OCDMA decoder first decodes the data and then data is fed to a turbo/ trellis decoder to retrieve the original information sent by the user. Each transmitter is assigned a unique codeword from an OCDMA address code. It is assumed that all the optical sources at transmitters are incoherent so that optical power signals of multiple users occurring at the same time would incoherently add in intensity at an OCDMA decoder.

In OCDMA systems, each data bit from a source is transformed into the desired destination codeword by using an OCDMA encoder. No light is actually transmitted when each data bit ‘0’ is issued by the data source. The BER performance of OCDMA systems is degraded mainly due to OMAI, Further identical data rates and signal formats are assumed for all the users and the same effective average power is assumed at the input of each receiver so that one user should not overwhelm the others [4]. In OCDMA systems, each data bit ‘1’ from a which comes from all other active users. At the receiver, the effects of thermal noise and APD noise have been considered. The binary bit ‘0’ might be mistaken for a binary ‘1’ if OMAI signals are strong enough to cause a false detection (called 0-error) at the receiver. But a false detection of the binary bit ‘1’ is not possible. This is because, with incoherent optical processing, light powers always add up [2-3]. OOCs are used as address codes in the simulation. An OOC is a family of (0,1) sequences with good auto and cross correlation properties i.e., the auto-correlation of each sequence exhibits the “thumbtack” shape and the cross-correlation between any two sequences remains low throughout.

The accumulated output of APD detector during each chip interval has been approximated as a Gaussian random variable [8]. The received optical signal intensity over a chip interval T_c is modeled as a Poisson point process. The average number of photons absorbed is $\lambda_s T_c$, where λ_s is the arrival rate of incident photons due to chip ‘1’ transmission in the signature sequence, which can be represented as:

$$\lambda_s = \eta P_w/hf \tag{1}$$

where

P_w received optical power at optical correlator.
η is the APD quantum efficiency.
h is the Planck’s constant.
f is the optical carrier frequency

The mean (μ) and variance (σ^2)of the conditional probability density function of the accumulated output of APD over the last chip interval can be expressed as:

$$\mu = GT_c[\varepsilon\lambda_s + I_b/ e] + T_cI_s/ e \tag{2}$$

$$\sigma^2 = G^2F_eT_c[\varepsilon\lambda_s + I_b/ e] + T_cI_s/ e + \sigma^2_{Th} \tag{3}$$

where

G is the average APD gain.
I_s is the APD surface leakage current
e is the electron charge.
F_e is the excess noise factor given by

$$F_e = K_{eff}G + (2 - 1/G)(1 - K_{eff}) \tag{4}$$

Where K_{eff} is the APD effective ionization ratio, σ^2_{Th} is the variance of the thermal noise and is given by:

$$\sigma^2_{Th} = 2K_BT_rT_c/(e^2 R_L) \tag{5}$$

where

T_r is the receiver noise temperature.
K_B is the Boltzmann’s constant.
R_L is the receiver load resistance.

III. Simulation details

In this paper, we have analyzed, simulated and compared the performance of uncoded OCDMA system (without error control coding), Turbo-coded OCDMA system and Trellis-coded OCDMA system. The conclusions derived are entirely based on the results of the simulations carried out for 10 active users. It is assumed that errors introduced are due to OMAI, thermal noise and APD noise. Simulation of OCDMA systems required the construction of OOCs. In addition, Turbo coded OCDMA systems required the construction of turbo encoding and turbo decoding functions whereas the Trellis coded modulation systems required trellis transmitter and receiver structures.

The simulation was carried out under the following assumptions:

1. The communication between the transmitters and receivers is pair wise.
2. Transmitter-receiver pair # 5 is the pair actually sending data and receiving data.
3. All other users send data bits that are randomly generated. Thus, the OMAI effect of all other users on transmitter-receiver pair # 5 is considered.
4. The effects of thermal noise and APD noise are considered.
5. The various transmitter-receiver pairs send data synchronously with respect to each other.

The data being sent by users other than user # 5 is assumed to be truly random. Therefore, with all specifications being the same, if the simulation is repeated, the bit error rate is bound to be different. Hence, to arrive at a generalized value of bit error rate for an OCDMA system with a particular set of specification, numbers of simulations were carried out and average results taken into consideration.

The generator matrix of recursive systematic encoder (RSC) employed by the turbo encoder used in the simulation is $G_R(D) = \begin{bmatrix} 1 & \frac{1+D+D^2}{1+D^2} \end{bmatrix}$ or (1, 7/5,7/5) in octal,

where feed forward generator $g_2(D) = 1+D+D^2$, feedback generator $g_1(D) = 1+D^2$. Fig. 1 gives the block diagram of the turbo encoder used in the simulation. The turbo decoder used in the simulation employs Max-logarithmic-MAP algorithm.

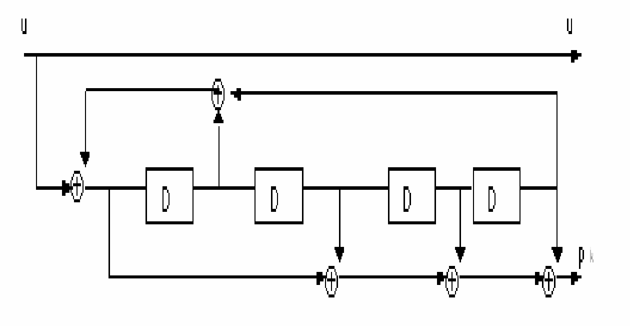

Fig. 1 Turbo Encoder

The architecture for the transmitter for trellis-coded scheme is given in Fig. 2[6]. The data frame has two slots to represent the state of the input data. If the information bit is same as the preceding digit, then it is encoded into the first slot. Once input data transits from 1 to 0 (or 0 to 1), then it is encoded into the second slot. Hereafter, the precoded data frame is sent to the optical sequence encoder in the upper arm or lower arm for spreading into signature sequence.

If the input data bit is 1, then data frame is transmitted through the upper arm. On the other hand if input data bit is 0, then data frame is transmitted through the lower arm. Thus there are four possible data symbols, and we denote them as α, β, γ and δ respectively. The precoded data symbols are illustrated in Fig. 2.

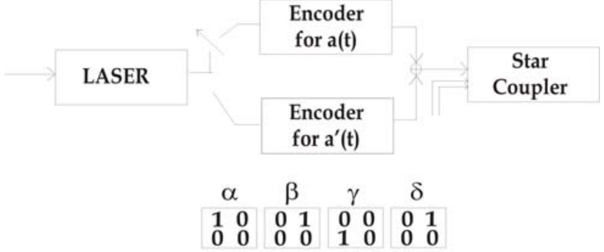

Fig. 2 Transmitter Architechture and Pre-Coded Data Symbol

If the input data bit is 1, then α is transmitted if previous bit was also 1, otherwise β is transmitted. If the input data bit is 0 then γ is transmitted if previous bit was also 0, therwise δ is transmitted. Fig.3 shows the resulting state transition diagram.

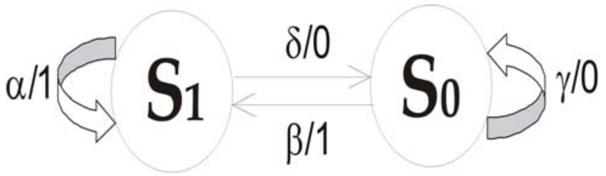

Fig. 3 State Transition Diagram

Each user is assigned, two mutually orthogonal signature sequences generated from time-shifted versions of OOCs. The correctness of the simulations was tested thoroughly by checking user data and user code words for each bit transmitted. For example: if all other users except user # 5 send only the data bit '0'. There will be zero OMAI and number of erroneous bits received should be zero and hence, BER would be zero. Receiver using double optical hard limiters and maximum likelihood sequence detector (MLSD) is shown in Fig 4.

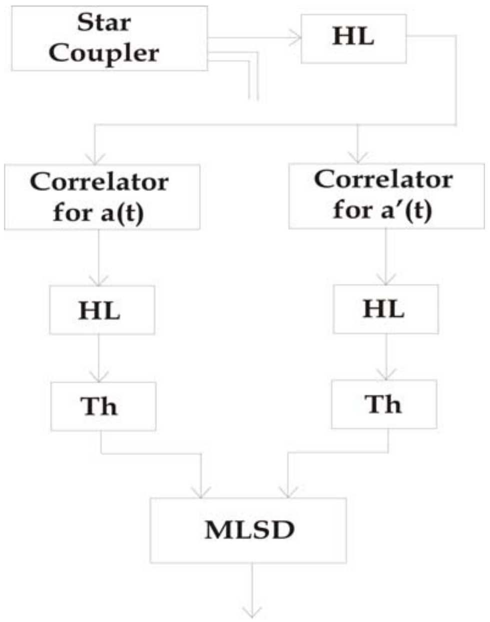

Fig. 4 Receiver using DHL and MLSD

IV. SIMULATION RESULTS

BER for various values of threshold for uncoded OCDMA, Turbo coded OCDMA and Trellis coded OCDMA systems are plotted. Figure 5 and 6 compare the BER performance of the uncoded OCDMA system with and without the use of double hard limiter. The system, which includes the double hard limiter, has an improved BER performance than a system without it as expected.

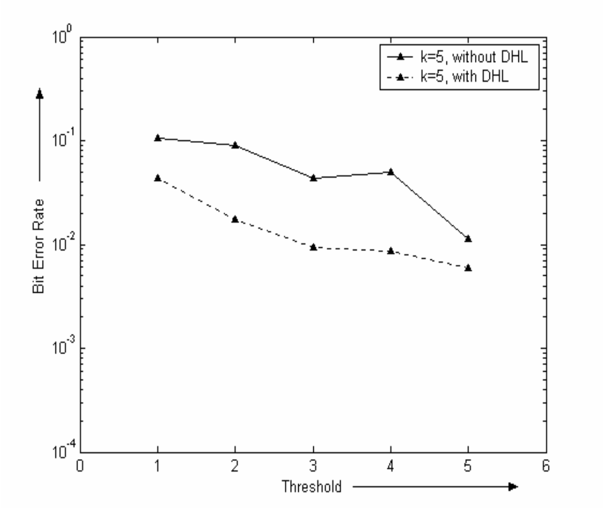

Fig. 5 Bit Error Rate versus threshold for OCDMA systems based on (100,5,1,1) OOC for fixed weight with and without DHL

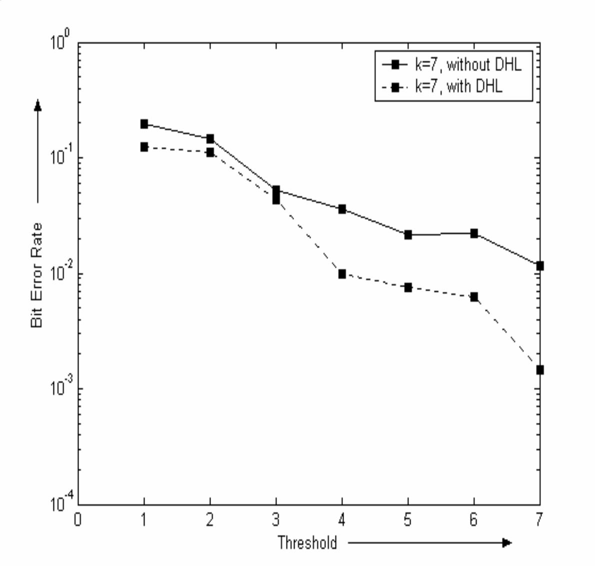

Fig. 6 Bit Error Rate versus threshold for OCDMA systems based on (100,7,1,1) OOC for fixed weight with and without DHL

Figures 7and 8, show the bit error rate performance versus threshold for OCDMA system employing optical orthogonal codes without coding, with Turbo coding and with Trellis coding.

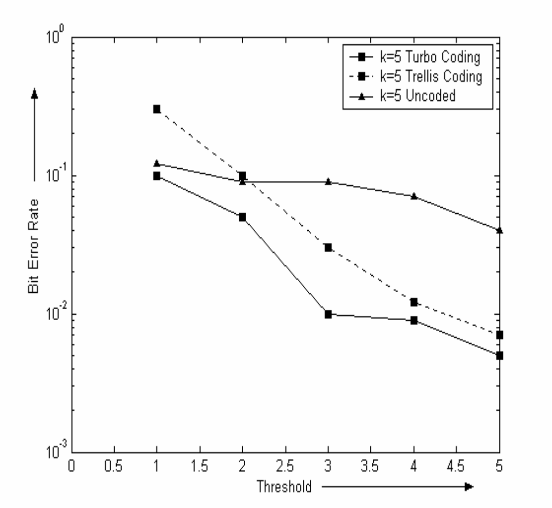

Fig. 7 Bit Error Rate versus threshold for OCDMA systems based on (100,5,1,1) OOC for fixed weight with Turbo Coding and with Trellis Coding

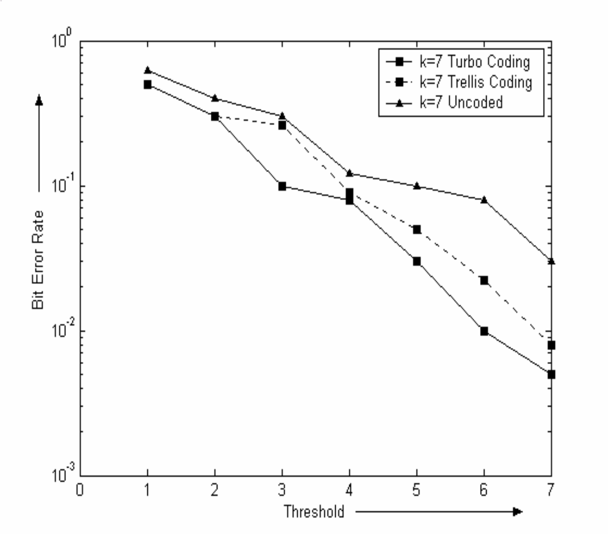

Fig. 8 Bit Error Rate versus threshold for OCDMA systems based on (100, 7, 1, 1) OOC for fixed weight with Turbo Coding and with Trellis Coding

From these simulations, we can infer that for a fixed weight, all the three systems have minimum BER performance when the threshold at the receiver is equal to the weight of the codes. A fixed weight Trellis coded or Turbo coded system is better than the uncoded system. Both Trellis and Turbo codes reduce the error floor.

The improvement in BER performance can be interpreted as gain due to coding. The decoders of both Turbo and Trellis codes account for the effect of OMAI, thermal and APD noise. The performance of Turbo coded system is found to be better than Trellis coded system. It is also observed that the system with higher code weight can yield better performance.

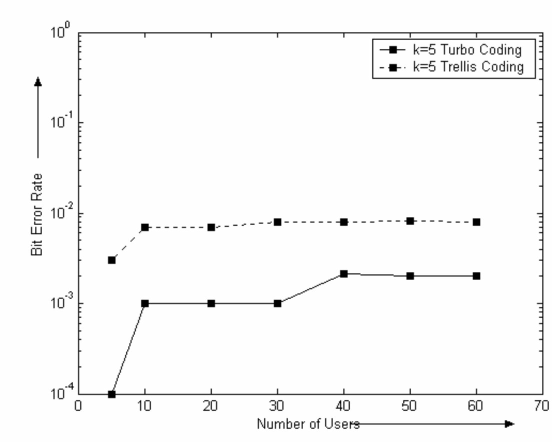

Fig. 9 Bit Error Rate performance versus Number of users for OCDMA systems based on (100, 5, 1, 1) OOC for fixed weight with Turbo Coding and with Trellis Coding

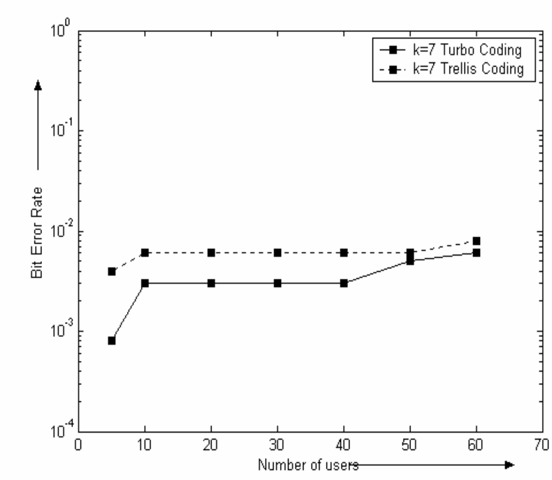

Fig. 10 Bit Error Rate performance versus Number of users for OCDMA systems based on (100,7,1,1) OOC for fixed weight with Turbo Coding and with Trellis Coding

From Fig. 9, we can observe the bit error rate performance of the system for a variable number of users, when we employ codes with a constraint length of 100 and weight of 5. Multiple access interference is the major deterioration source for the system performance. It can be seen that an increased number of users will cause a penalty on the system performance, in either coding schemes. It can be observed that for lesser number of users the BER performance is better. From Fig. 10, we can observe the bit error rate performance of the system for a variable number of users, when we employ codes with a constraint length of 100 and weight of 7. Although the increase in code weight provides somewhat of an increased performance the change is not very significant.

V. CONCLUSIONS

The performance analysis of Turbo-coded OCDMA system and Trellis-coded OCDMA system was accomplished and a comparison between the two systems was made. The simulation results show that the BER performance of Turbo-coded systems is better than that of the Trellis-coded systems. Nevertheless the Trellis- coded system is better than the uncoded OCDMA system. The BER for both the coded systems is observed to increase as the threshold decreases below its ideal value, which is the weight of the OOC. As the number of users increase, the performance of both Trellis-coded and Turbo-coded systems appears to degrade. We can thus propose that the Trellis-coded system can find applications in systems where bandwidth is a crucial factor, decoding time has to be kept low and high reliability is not a constraint. Also the hardware complexity of a Trellis-coded OCDMA system is comparatively less as compared to a Turbo-coded OCDMA system. It can be used without much modification of the existing chipsets. It is ideal for LAN applications. Turbo-coded systems should be used where reliability is very important. However, bandwidth used in Turbo-coded systems is more than that used for a Trellis-coded system.

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