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BER and total Throughput of asynchronous DS-OCDMA/WDM systems with Multiple User Interference

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The BER and Throughput of Direct-Sequence OCDMA/WDM systems based on quadripolar codes and superstructured fiber Bragg gratings are statistically derived under asynchronous operation, intensity detection, and Multiple User Interference. Performance improvements with Forward Error Correction are included.

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Introduction

Optical Code Division Multiple Access (OCDMA) is an alternative technology for future optical networks. Synchronous or asynchronous operation, flexible bandwidth management, and network scalability are potential advantages. In SuperStructured Fiber Bragg Grating (SSFBG) Direct Sequence (DS-) OCDMA, data bits are coded/decoded in the time domain using signature sequences embedded in the amplitude or phase of the grating. 255 chips, 320 Gchip/s, 4 phases optical encoding was experimentally demonstrated [1] and synchronous 4 OCDMA x 4 WDM x 311 Mb/s operation was proven [2].

Asynchronous operation of highly OCDMA-multiplexed, mixed systems is an appealing upgrade known to reduce system complexity. Coherent Multiple User Interference (MUI) with intensity photodetection, however, limits the number of OCDMA users in this case [3]. In this work, the corresponding MUI-limited BER and throughput are compared, and performances including Forward Error Correction (FEC) over the OCDMA channels are presented too. Trade-offs between channel bit rates R, number of OCDMA users N, WDM wavelengths W, and SSFBGs manufacturing issues are outlined.

System model

A simplified asynchronous system model is considered. The OCDMA system is characterized by discrete correlation sequences, and the only source of performance degradation is MUI. The characteristics of the optical channel (optical source, encoding-decoding imperfections, propagation, amplification) are neglected. Optical, shot, and thermal noise at the receiver are also neglected. Equi-polarized signals are assumed in order to get the worst interference case. N users are assumed to transmit statistically independent bit sequences with identical bit rate R, power, and symbol probability. Each bit is phase-encoded using a L-long, quadripolar codeword, and the resulting sequence is eventually zero-padded according to the channel utilization CU. Given the chip duration T_{chip}, the effective bit rate is set to $R = CU/(2L+1)T_{chip}$, so that correlation sequences of successive data bits on a given channel do not overlap and no self-interference occurs. The N different correlation signals are interfering coherently at the receiver, which is simply modeled by an infinite bandwidth intensity photodetector, electrical threshold, and decision circuit. The asynchronous OCDMA operation and the incoherent nature of different sources are modeled by assuming the corresponding correlation time lags and absolute phases are independent and uniformly distributed. The system performance has been studied following a gaussian approximation similar to [3] (Fig. 1, dashed). To improve the accuracy of the analysis for low number of users, the actual probability distributions at the receiver have been derived by extending the approach in [4] in order to properly model an intensity photodetector when random phase, random amplitude signals are interfering. Statistical averaging in the few-user approximation is obtained by averaging six different sets of interfering sequences for each value of L and CU. The results are also shown in Fig. 1 (solid). Good agreement between the two approaches is apparent and improves as N increases.

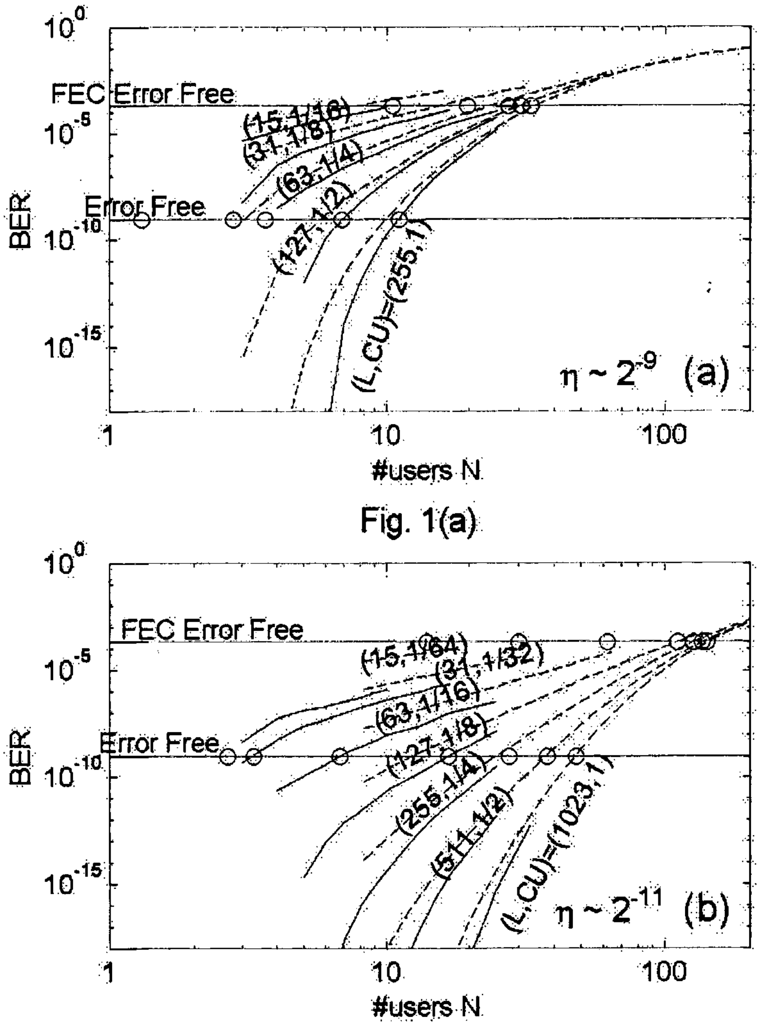

Fig. 1(a)

Fig. 1(b)

Fig. 1: BER vs. N: (dashed) gaussian approximation; (solid) exact. Single-channel bandwidth efficiency η is fixed: (a) $\eta = 2^{-9}$ [1]; (b) $\eta = 2^{-11}$.

Simulation results

The graphs in Fig. 1 present two different values of the per-channel bandwidth efficiency $\eta = RT_{chip} = CU/(2L+1)$ (in b/s/Hz/channel). In (a), the performance of a system experimentally demonstrated ($L = 255$, $CU = 1$, $T_{chip} = 3.2$ ps, $R = 1.25$ Gb/s [1]) is shown. Without FEC, $N = 11$ users are multiplexed using an optical bandwidth $\delta\lambda \sim 6$ nm. Using a Reed-Solomon RS

(255,239) FEC code, the error free level is raised to BER ~ 2×10^{-4} and N is increased to 33. It is apparent that, for fixed η, increasing L is much more effective than decreasing CU [3]. However, this results in an increased grating manufacturing complexity, since longer codes = longer gratings = more stringent requirements in grating writing and packaging. The number of OCDMA users N multiplexed with error free performances is increased by decreasing η, i.e., by using shorter T_{chip} (increased optical bandwidth $\delta\lambda$), or by reducing the bit rate R transmitted via each OCDMA channel. The first solution is compatible with standard optical TDM frames and keeps the grating length short. Current SSFBG technology limitations restrict the minimum chip duration to $T_{chip} \geq 1.6$ ps. Limiting the practical grating length L_{gr} to tens of centimeters, the longer L achievable is 1023, corresponding to $L_{gr} \sim 17$ cm, $\delta\lambda \sim 12$ nm, and $\eta = 2^{-11}$ (with bit rate $R = 311$ Mb/s). The corresponding OCDMA performances are shown in Fig. 1(b), giving $N = 48$ without FEC and up to $N = 140$ with FEC.

Since the increase in the number of OCDMA channels N is obtained by reducing the per-channel bandwidth efficiency η, it is important to check the overall throughput of a mixed OCDMA/WDM system given the available bandwidth. It has been experimentally proven [2] that WDM channels can be multiplexed with acceptable power penalty if the channel spacing $\delta\lambda$ is larger than the spectral width of the main lobe of the encoded sequence. Under this assumption, the system throughput as a function of N is shown in Fig. 2 both without FEC (a) and with FEC included (b) considering a standard EDFA bandwidth $BW = 35$ nm (~4.32 THz). Solid, dotted, and dashed lines represent points at same L, CU, and η, respectively. The graphs in Fig. 2 are scalable, each point corresponding to a multitude of (R, W) combinations. The exact R and W are derived once T_{chip} is defined. For the considered EDFA bandwidth, $2W/T_{chip} = BW$. T_{chip} and L also define the actual L_{gr}.

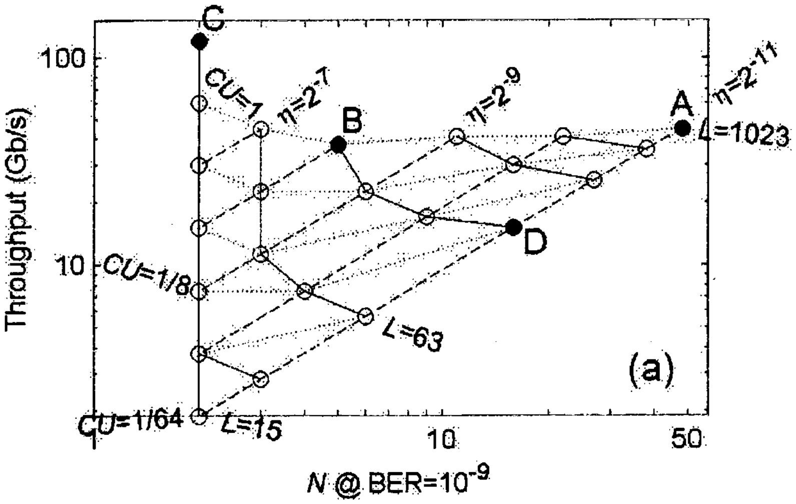

Fig. 2(a)

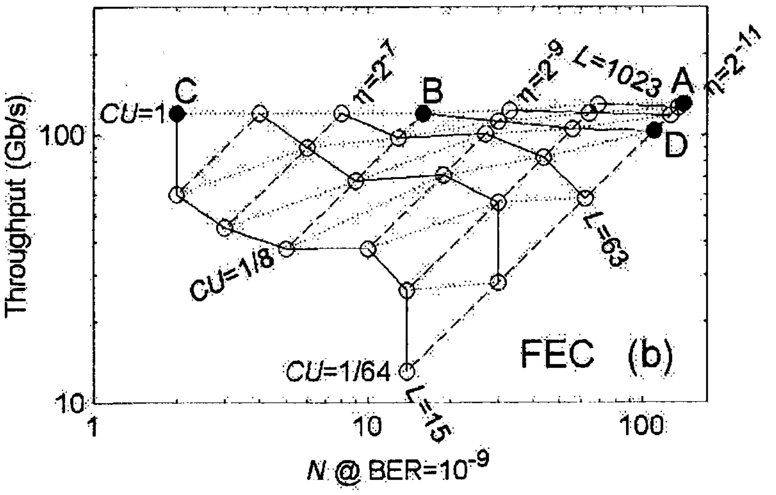

Fig. 2(b)

Fig. 2: Error free Throughput (in Gb/s) vs. *N* for a mixed OCDMA/WDM system without FEC (a) and with RS (255,239) FEC (b). The optical bandwidth is 30 nm. (Solid) equal *L*; (dotted) equal *CU*; (dashed) equal η.

At a given T_{chip} and for $CU = 1$, a throughput variation within ~10% is obtained over a wide range of *R* and *N* values in both Fig. 2(a) and (b). If $T_{chip} = 1.6$ ps is considered, $W = 3$ wavelengths each with 48 (140) x 311 Mb/s channels (A) or 5 (16) x 2.5 Gb/s channels (B) can be transmitted with a throughput of 45 to 38 Gb/s (132 to 120 Gb/s) (FEC values in brackets). If higher data rates $R = 20$ Gb/s are considered (C), the almost TDM/WDM system without FEC presents much higher throughput, but lacks the flexibility given by OCDMA since only 2 users are multiplexed. If FEC is used, no gain is obtained by further increasing R towards point C.

In order to compare performances at different chip durations T_{chip} - WDM wavelengths W, but the same bit rate R, let us consider $T_{chip} = 1.6$ ps, 1.44 THz grid, $W = 3$ (case 1) and $T_{chip} = 12.8$ ps, 180 GHz grid, $W = 24$ (case 2):

- $R = 311$ Mb/s (low bit rate): cases 1 and 2 correspond to A and B in Fig. 2, respectively. As already commented, the resulting throughputs are almost equivalent. Higher OCDMA flexibility (A) requires longer and more complex gratings (even though $L_{gr} \sim 17$ cm for $L = 1023$ is still acceptable).
- $R = 2.5$ Gb/s (high bit rate): now cases 1 and 2 correspond to B and C, respectively. Without FEC, the higher throughput WDM solution (C) is preferable, since N is comparably small in both cases. With FEC, the throughput is comparable and the OCDMA solution (B) starts to become attractive since 16 OCDMA users are possible. Grating length is not an issue ($L_{gr} \leq 17$ cm).

In case 2, very low bit rates implementations (down to $R = 39$ Mb/s for $\eta = 2^{-11}$) with high values of N are potentially achievable. But, due to the grating length limitation assumed so far, only points below the B-D line have to be considered. A 60% throughput penalty (38 Gb/s to 15 Gb/s) results in moving from B ($R = 311$ Mb/s) to D ($R = 39$ Mb/s) in Fig. 2(a). Conversely, the throughput loss is limited to ~10% with FEC (120 Gb/s to 103 Gb/s).

Discussion and conclusions

Using a statistical analysis, the throughput of an asynchronous SSFBG DS-OCDMA/WDM system in error free conditions has been derived for a wide range of code/grating lengths, bit rates, WDM wavelengths, and OCDMA channels numbers. Network flexibility and reduced

TDM complexity are obtained in a largely OCDMA-oriented system by using a high number of OCDMA channels and asynchronous operation. High flexibility in the choice of the number of OCDMA channels (up to 45) and WDM wavelengths is obtained with limited throughput variation for data rates in the 311-625 Mb/s range. However, this approach results in very inefficient bandwidth utilization (almost two order-of-magnitude worse than up-to-date TDM/WDM experiments) due to coherent MUI and intensity photodetection. Using a 35 nm bandwidth, the throughput is limited to 45 Gb/s, but it is increased to 130 Gb/s if RS (255,239) coding is applied to the data stream. This solution is appealing in LAN environments with low bit rates implementations where cost effectiveness is preferable to bandwidth efficiency. In this framework, very low bit rates ($R < 100$ Mb/s) with high number of OCDMA channels ($N > 100$) are a possible option with long chip durations and high levels of WDM multiplexing. A ~50% performance improvement is forecasted with randomly polarized channels, and further advantage is obtained by nonlinear optical thresholding at the detector.

Higher bit rates are achieved only with very short chip durations ($T_{chip} = 1.6$ ps) and with a limited number of OCDMA channels ($N < 10$), and no advantage over standard WDM/TDM systems is seen. In this context, the use of few, synchronous OCDMA channels with optical gating and optical hard thresholding (reduced effect of MUI, but high complexity) is a preferable solution since it increases the bandwidth efficiency in DWDM/TDM systems [5].

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