Performance Comparison of Coherent Ultrashort Light Pulse and Incoherent Broad-Band CDMA Systems

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***Abstract*—In this letter, we compare the theoretical bit-error-rate (BER) performance limits of coherent ultrashort light pulse and incoherent broad-band code-division multiple access (CDMA) communication systems. Our comparison highlights the fundamental differences in the scaling of BER and throughput with important system parameters. The results indicate that for the same optical bandwidth and BER, an ultrashort pulse CDMA with a code length of 512 can in principle yield a substantial throughput advantage over the incoherent broad-band systems.**

***Index Terms*—BER performance limits, incoherent broad-band CDMA, ultrashort pulse CDMA.**

RECENTLY, there has been considerable research activity on optical code-division multiple access (O-CDMA) and key developments and experimental advances of several O-CDMA schemes were discussed in [1]. The schemes based on coherent processing (manipulation of optical *fields*) seems to be most promising for local area access or network applications. Coherent processing may be achieved using either incoherent (e.g., amplified spontaneous emission) or coherent (modelocked pulse) broad-band optical sources, together with appropriate receiver structures. O-CDMA approaches using incoherent sources, such as coherence multiplexing [2] and spectral amplitude coding [3], [4] called incoherent broad-band CDMA (INC-CDMA) offer the advantage of simpler technology. However, recent analyses have shown that INC-CDMA approaches are limited to throughputs of $\sim$10$-$50 Gb/s [1], [2], [4]. On the other hand, an analysis of ultrashort pulse CDMA (US-CDMA) using spectral phase coding of coherent ultrashort pulses predicted that throughput could in principle exceed 100 Gb/s [5], although realization of the full potential of this scheme requires advanced femtosecond technology (see experiments in [6]–[8]) and is still a research challenge.

In this letter, we perform the first comparison of the theoretical bit-error-rate (BER) and throughput performance of INC-CDMA and US-CDMA schemes for a common set of system parameters and explain the difference in predicted performance using the asymptotic BER expressions. In the system performance comparison, we assume that both systems have sources with Gaussian line shapes with identical widths and all the users employ asynchronous transmission and identical bit rates. The only source of degradation considered in this evaluation is the effect of noise due to multiple users. Our results indicate that an US-CDMA scheme with longer code lengths offers a significant throughput advantage and a fundamentally better scaling behavior with the number of users compared to INC-CDMA systems.

The topology of US-CDMA and INC-CDMA systems is based on a broadcast local area network architecture, in which signals from all transmitters (users) are distributed to every receiver using a passive star coupler. Although the system aspects were described in many articles [1]–[6], here we briefly narrate these systems. In an US-CDMA system, the laser pulses having pulsewidths of τ_p (FWHM) and a bit period T_b are modulated by using conventional on–off-keying (OOK) and then spectrally encoded by a spectral phase encoder that results in a train of coded (pseudonoise) pulses. These coded pulses have a duration $T = N_0\tau_p$, where N_0 is the length of the spectral phase code. Only the intended receiver with a matching code can successfully decode the encoded signals back into ultrashort pulses. The incorrectly decoded signals corresponding to the unmatched code remain as low intensity pseudonoise bursts called multiple access interference (MAI). An ultrafast optical thresholder is assumed to extract the correctly decoded signals in the presence of MAI. We define a parameter $K = T_b/T$ ($\geq$1) as a statistical multiplexing factor in an US-CDMA system. This parameter K would correspond to a unity value in INC and other optical CDMA systems, meaning that all the users overlap spectrally and temporally on each bit transmitted.

We now briefly describe the INC-CDMA schemes. The encoders and decoders in a spectral amplitude coding system [3] are similar to that of US-CDMA system, except that they employ spatially patterned amplitude masks in place of phase masks. Additionally, data is transmitted in spectral amplitude coding systems either using direct intensity modulation of the LED according to amplitude-shift keying (ASK) scheme or by transmitting one of two complementary codes [4]. Two spectral amplitude masks (one complementary) along with balanced photodetectors are used at the receiver to recover the transmitted data. On the other hand, the encoding and decoding operations in a coherence multiplexing system use unbalanced Mach–Zehnder interferometers with differential delays that exceed the coherence time of an ASE light source

Manuscript received April 26, 1999; revised August 16, 1999. The work of A. M. Weiner was supported by the National Science Foundation under Grant 9626967-ECS.

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Publisher Item Identifier S 1041-1135(99)09516-6.

[2]. Each encoder in a coherence multiplexing system includes an external digital phase modulator and the data is keyed based on a phase-shift keying (PSK) scheme. The transmitted data is decoded by matching the differential delay of the decoder to that of the encoder. The technology requirements of the INC-CDMA systems are less severe than for the US-CDMA system and the systems utilize commercially available direct detection balanced photoreceivers.

The BER performance of an US-CDMA system employing an ideal threshold device was rigorously analyzed in [5]. An ideal thresholder was assumed to be a nonlinear optical device which completely transmits (suppresses) the optical signal whenever the instantaneous intensity exceeds (does not exceed) the threshold value. Hence, the BER is determined by the instantaneous intensity statistics, which is negative exponential for the multiaccess interference (MAI) assuming random spectral phase coding [5]. Electronics in the receiver examine the output of a nonlinear device over a duration $\beta\tau_p$, where $\beta = \tau_R/\tau_p$ is the "broadening factor" due to the relatively slow response of a photoreceiver, with an impulse response (FWHM) τ_R. The value of β would be unity by assuming an ultrafast photoreceiver with $\tau_R = \tau_p$; and its value would be around 1100 assuming $\tau_p =$ 88 fs and a 10 Gb/s commercially available photoreceiver (impulse response in the order of 100 ps). The asymptotic BER expression for US-CDMA system assuming a large signal-to-noise ratio (SNR) condition and a threshold set near optimum is obtained by simplifying the exact system BER expression derived in [5], yielding

$$\mathrm{BER_{US}} \approx \frac{\beta}{2}\sum_{l=1}^{M-1} p(l)e^{-\frac{N_0 I_{Th(\mathrm{opt})}}{l}} \qquad (1)$$

where $\beta e^{-N_0 I_{Th(\mathrm{opt})}/l}$ represents the false alarm error probability over β sampling instants and l denotes the number of interfering signals overlapping at a particular instant of time. The parameter M denotes the total number of users and $I_{Th(\mathrm{opt})}$ represents the optimum receiver threshold normalized to the peak power (P_0) of a properly decoded pulse. The probability $p(l)$ that l interfering signals overlap at a particular instant of time depends on M and K and follows a binomial distribution given by [5]

$$p(l) = \binom{M-1}{l}\left(\frac{1}{2K}\right)^l\left(1-\frac{1}{2K}\right)^{M-1-l}. \qquad (2)$$

The number of overlapping signals is usually much less than the total number of users ($l \ll M$) since K has a relatively large value. The missed detection error probability has been neglected in (1) due to the large SNR condition, for which false alarms dominate the BER expression at the optimum threshold setting. The $I_{Th(\mathrm{opt})}$value most noticeably depends on β and N_0 and changes only slightly with M and K, because a small value of l dominates the BER expression. For example, if $K = 100$, $M = 10$, and $N_0 = 128$, then $I_{Th(\mathrm{opt})}$ computed numerically from the exact BER expression in [5] corresponds to 0.275 at $\beta = 1$ and increases slowly to 0.35 for $\beta = 1100$. When N_0 is increased to 512, $I_{Th(\mathrm{opt})}$ is approximately 0.3 for β =1100.

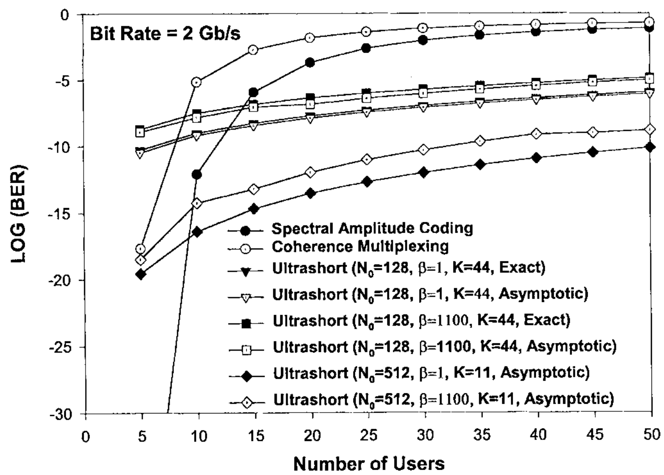

Fig. 1. BER performance comparison of US-CDMA and INC-CDMA systems for bit rate of 2 Gb/s and a source spectral width $\Delta\lambda = 40$ nm (corresponds to a coherence length of 132 fs and ultrashort pulsewidth of 88 fs) at the optimum receiver threshold (numerically optimized) settings. Also shown is the comparison of BER performance of an US-CDMA system using the exact and asymptotic error-rate expressions for different code lengths (N_0) and statistical multiplexing factors (K).

The asymptotic BER results are compared with the exact BER results of [5] in Fig. 1 for bit rate = 2 Gb/s, $N_0 = 128$ with $\beta = 1$ and 1100 and it can be seen that they are in good agreement. It is also useful to discuss the SNR in an US-CDMA system, which we take as the square of the signal intensity (P_0^2) divided by the variance of MAI. Assuming l interfering signals at a given instant of time, the statistics of MAI follows a negative exponential distribution with variance $(lP_0/N_0)^2$. Thus, the SNR in an US-CDMA system is $\mathrm{SNR_{US}} \approx N_0^2/l^2$.

The BER analysis of INC-CDMA systems [2]–[4] showed that the system throughputs are limited by the beat noise components arising due to incoherent fields falling on a photodetector. Although any particular sample of the intensity has negative exponential statistics [9], the detected noise consists of the sum of a large statistically independent samples over the entire bit period, which constitutes many coherence times, resulting in Gaussian statistics. This is a consequence of the receiver bandwidth being much smaller than the optical bandwidth. Hence, the BER expression for INC-CDMA systems is given by [2]–[4]

$$\mathrm{BER_{INC}} = Q\left(\sqrt{\mathrm{SNR_{INC}}}\right) \qquad (3)$$

where $Q(x) \approx e^{-x^2/2}/2x\sqrt{\pi}$ is the Gaussian integral function [10] and $\mathrm{SNR_{INC}} \approx \Gamma/\tau_c B_e l^2$ is called the optical beat noise limited SNR [2], [4]. The parameter $\Gamma = 0.664$ for the spectral amplitude CDMA and $\Gamma = 0.25$ for the coherence multiplexing system and τ_c denotes the coherence time of the source. Data modulation by code complementation [4] is assumed for spectral amplitude coding. The parameter l in INC-CDMA systems is essentially the same as the total number of users M. Now, using $Q(x)$ and $\mathrm{SNR_{INC}}$ expression in (3), the asymptotic BER expression for INC-CDMA systems can be written as $\mathrm{BER_{INC}} \approx \sqrt{(\tau_c B_e l^2/2\Gamma\pi)}e^{-\Gamma/2\tau_c B_e l^2}$. Now, comparing $\mathrm{BER_{INC}}$with (1), we see that the exponentials in the BER expressions scale differently with l. Additionally, we note that the SNR expressions of US-CDMA and INC-CDMA systems are both proportional to l^{-2}, and therefore for comparison purposes, we define an equivalent code length for INC-CDMA as $(N_0)_{eq} \approx \sqrt{\Gamma/\tau_c B_e}$. Using typical values $\tau_c = 100$ fs, $B_e = 1$ GHz, we have $(N_0)_{\text{eq}} \approx$ 50–80, which is comparable to the practical code lengths $N_0 = 64$–128 currently used for experimental tests of US-CDMA (see [6]–[8]). Thus, although the equivalent code lengths are comparable, US-CDMA has some advantage due to the higher statistical multiplexing factor K, which is not available in INC-CDMA systems. More importantly, the US-CDMA offers the possibility of longer code lengths, since N_0 is not coupled to the data rate. In INC-CDMA, the, equivalent code length mainly depends on the ratio of the optical bandwidth to the electrical bandwidth and can not be easily increased without decreasing the bit rate.

The system BER as a function of the number of users is shown in Fig. 1 for a bit rate of 2 Gb/s assuming a source spectral width $\Delta\lambda = 40$ nm centered at 1.55 μm. Equations (1) and (3) were utilized to calculate the BER performance of US-CDMA and INC-CDMA systems, respectively, where we use $\tau_p = 0.44/\Delta\nu$ and $\tau_c = 0.664/\Delta\nu$, and $\Delta\nu$ is the optical bandwidth. It can be seen that the INC-CDMA systems yield a lower BER in the small number of users regime, while the US-CDMA system with statistical multiplexing factors K of 11 and 44 offers lower BER in the large number of users regime for β in the range of 1 to 1100. However, US-CDMA system BER is increased by 1–1.5 orders of magnitude with $\beta = 1100$ over an ideal system (but not attainable) that has a unity β. It is also seen that the BER performance of an US-CDMA can be improved by several orders of magnitude by increasing the code length of the spectral phase encoder from 128 to 512. Note that increasing the code length N_0 results in a reduced K factor. Our results show that the lowest error rates are always obtained for the largest N_0 possible; thus, the reduction in the average background intensity noise per user due to a longer code length has a much stronger effect than the reduction in K factor. This trend was also observed in [5].

It is interesting to compare the number of users versus the bit rate for INC-CDMA and US-CDMA systembs to achieve a BER$=10^{-9}$ from which the system throughout (bit rate times number of users) can be evaluated. Numerical calculations reveal that the throughputs of INC-CDMA systems are limited to the range of 10–50 Gb/s systems assuming a source spectral width $\Delta\lambda = 40$ nm when the user bit rate is varied from 1 to 10 Gb/s. The US-CDMA system using a code length of 128 (for which K ranges from 88 to 8.8) results in comparable throughputs. If the code length in an US-CDMA system is increased to 512 (for which K ranges from 22 to 2.2), then the throughput can be maintained within the range of 76–120 Gb/s even with $\beta = 1100$, which yields a significant improvement over INC-CDMA systems.

Fig. 2 shows the system throughput versus the number of users for INC-CDMA and US-CDMA systems to achieve a BER $= 10^{-9}$. As reported in [2] and [4], throughput of an INC-CDMA system is $\Lambda/\tau_c l(\text{SNR}_{\text{INC}})$ which decreases inversely with the number of users, where $\Lambda = 1.32$ for spectral amplitude coding and $\Lambda = 0.5$ for coherence multiplexing. In contrast, the throughput of an US-CDMA system is almost flat with an increase in the number of users. This scaling behavior is a significant fundamental difference between US-CDMA and INC-CDMA schemes.

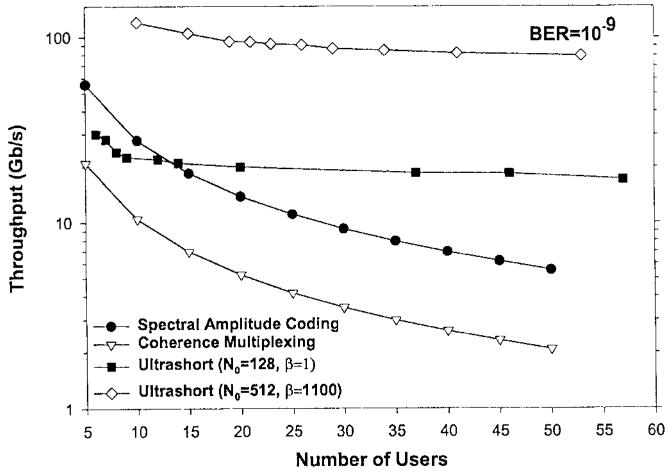

Fig. 2. Throughput (log scale) versus the number of users for coherent ultrashort pulse CDMA, coherence multiplexing, and spectral amplitude CDMA systems assuming a source spectral width $\Delta\lambda = 40$ nm (corresponds to a coherence length of 132 fs and ultrashort pulsewidth of 88 fs) for a BER $= 10^{-9}$or SNR$_{INC} = 36$ at the optimum threshold (numerically optimized) settings. For US-CDMA system, the corresponding statistical multiplexing factor K varies from 88 to 8.8 for $N_0 = 128$ and 22 to 2.2 for $N_0 = 512$.

In conclusion, our analysis revealed the fundamental differences between the US-CDMA and INC-CDMA systems relating to the scaling of BER and throughput with the number of users. For the same optical bandwidth and BER, an US-CDMA with a code length of 512 can in principle yield a significantly higher throughput than INC-CDMA systems.

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