Hybrid pulse position modulation/ultrashort light pulse code division multiple access for data networking

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ABSTRACT

Future data networks are required to support numerous high-capacity connections while providing simplified management and connectivity. To meet these requirements, we propose to utilize broadband ultrashort light pulses (ULP) in conjunction with pulse position modulation (PPM) as an efficient modulation format and code division multiple access (CDMA) for interference suppression. This networking format is operated asynchronously for simplified control, and requires minimal management for ensuring that the number of active users is below the limit at which multi-user interference generates excessive errors. The pulse positions can be detected at the receiver with high temporal resolution by utilizing a time-to-space conversion operating in real-time. The performance of the PPM/ULP-CDMA is found to depend on the following parameters: the ULP duration, the bandwidth of each spectral chip of the CDMA filter, and the ULP repetition time. We find that employing PPM improves the performance of the system relative to On-Off Keying (OOK). The performance can be further improved by increasing the number of PPM symbols, reducing the spectral chip bandwidth, and reducing the ratio of the pulse duration to repetition time. The performance analysis shows that the proposed system operates at a high bandwidth efficiency.

Keywords: ultrashort pulse, ultrafast optics, femtosecond pulse, code division multiple access, pulse position modulation, data networking, next generation internet, spatial-temporal processing, space-time conversion.

1. INTRODUCTION

It is commonly felt that a fiber-based optical communication network is the only way to meet the drastically increasing demand for multimedia services in the near future. Although wavelength division multiplexing (WDM) is the current favorite multiplexing technology for optical communication, CDMA can be a desirable alternative since it would provide asynchronous access to a network, a degree of security against interception, no need for either frequency (or time) allocation or guard bands because of complete utilization of the time and frequency by each user, and simplified network control.

CDMA encoding of ultrashort light pulses for optical communication was first suggested by Weiner, Heritage, and Salehi.[1,2] The technique is based on broadcasting encoded waveforms generated by spectral filtering an ultrashort pulse with an orthogonal phase code set. Each user uses a unique phase code from the orthogonal set for encoding a pulse before transmission on a common optical fiber carrier in an On-Off Keying (OOK) modulation format. The desired signal is restored to a short pulse form (i.e., decoded) at the receiver by applying a spectral filter consisting of the phase-conjugate code used at the transmitter of interest. The optical waveforms from other communicating members remain as encoded pulses with long duration and low intensity. The decoded signal is detected by a non-linear thresholding operation,[3] as the temporal variation of the signal is too fast for electronic detection schemes.

Using real-time spatial-temporal processors in conjunction with the CDMA encoding format can provide new degrees of freedom in the design of the communication system. The ability to spatially observe the temporal signal over a finite time window with a time-to-space converter[4] enables more sophisticated data modulation formats to be considered. In this paper, pulse position modulation (PPM) as a method of transmitting more than one bit of information per pulse is suggested (see figure 1). The receiver detects all possible positions where a data pulse may exist and selects the position that registers the strongest signal. The transmitter transmits the data encoded pulse at one of M possible positions, thereby encoding $\log_2 M$ bits of information per pulse. Additionally, the signal conversion cancels the need for nonlinear thresholding, as the time filtering can be easily implemented with a spatial filter in the form of a slit on the converted spatial signal. By using the PPM format, both the single user and the aggregate capacity of the communication network increases.

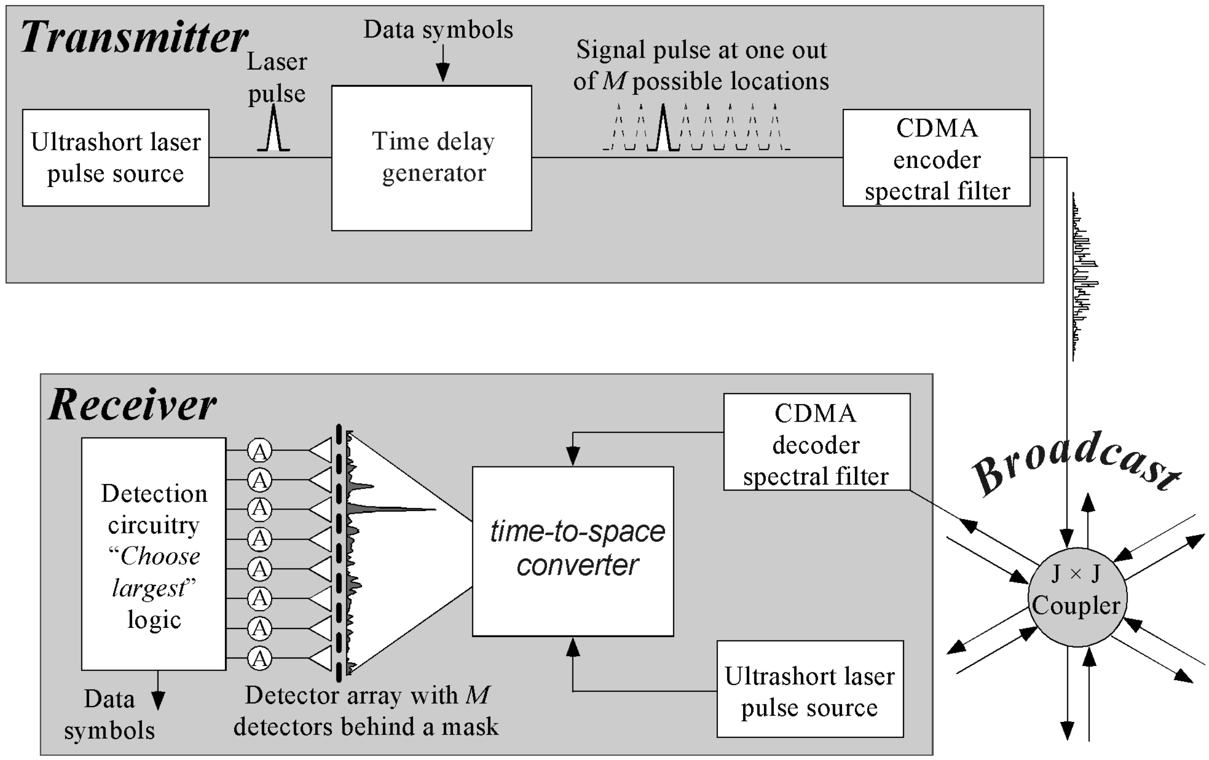

Figure 1: Proposed hybrid PPM/CDMA transmission format. PPM is utilized as an efficient data modulation scheme and CDMA encoding for interference suppression in an asynchronous networking environment.

2. SYSTEM DESCRIPTION AND ANALYSIS

In the ULP-CDMA communication format, each user encodes his transmitted pulse with a unique spectral filter. The spectral filter is comprised of contiguous rectangular frequency bands, each of bandwidth Ω, where each band is encoded by a phase value prescribed by a coding sequence. The encoding filter can be realized in a spectral processing device, traditionally performed in a free-space optical setup consisting of diffraction gratings and lenses,[5] or in an analogous arrayed waveguide grating implementation.[6] The spectral filter can be implemented by an etched phase mask or a spatial light modulator placed in the central Fourier plane of the processors, where the spectral components of the input ultrashort pulse are spatially dispersed. The filter dephases the spectral components of the short pulse, yielding a random waveform whose duration is proportional to $1/\Omega$, which is much longer than the input ultrashort pulse duration. We have investigated the statistical properties of these encoded waveforms, and found that they can be modeled as zero-mean, nonstationary, complex Gaussian processes conditioned on knowledge of the transmission time (to be reported elsewhere). One of the results of our analysis is that the *effective number* of code elements contained in the bandwidth of the short pulse is found, which will be an important parameter in the design of frequency domain CDMA communications. This effective number defines the expected reduction in peak power of the CDMA encoded ULP, similar to the processing gain in spread-spectrum communication.

Using space-time processors in the terminal equipment of a network, it is possible to employ a more efficient modulation format as PPM. The data encoded pulse can be transmitted at any position within the time window of the processors. The pulse separation time between adjacent time slots, T_{ps}, is set to the minimal value that maintains negligible crosstalk between positions (to preserve signaling orthogonality), and M such positions are supported in the time window of the processors (i.e., must be as long as $M \cdot T_{ps}$). Therefore, a new pulse is generated at the transmitter's mode-locked laser every T_s seconds (defining the symbol period), shifted to the desired position by a space-to-time converter in accordance to $\log_2 M$ bits of information, and CDMA encoded prior to transmission on the shared network. The received signal, consisting of the transmissions of all users, is CDMA decoded, despreading the desired pulse only, and detected by a photo detector array in the time-to-space converter. Electronic circuitry performs the required logic for selecting the position with the strongest signal component, thereby extracting the data behind the pulse position modulation. Another implementation of PPM/CDMA

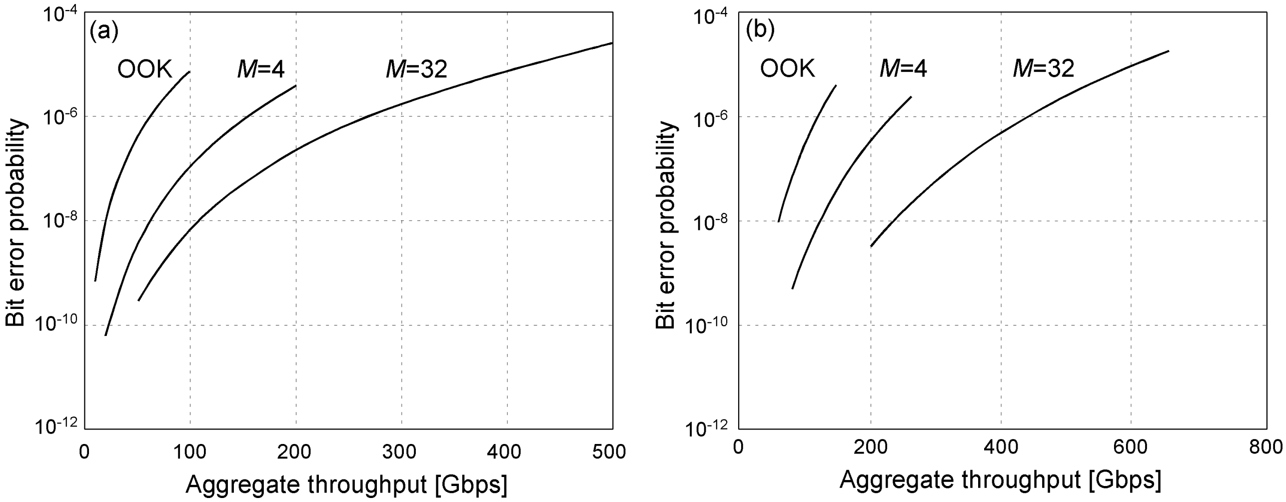

Figure 2: BER curves of PPM/CDMA format for 200 fs pulses and symbol period 10 ns. (a) Spectral bandwidth of 50 GHz, N_{eff}=94, and (b) spectral bandwidth of 25 GHz, N_{eff}=188. Note different abscissa scaling.

has been recently proposed without the use of spatial temporal processing, based on increasing the symbol period to a multiple of the pulse source repetition time.[7] This latter method required a high repetition rate, mode-locked laser for sufficient throughput per user.

The performance analysis of the communication system is based on detection errors due to inter-user interference only, as it is the dominant source of degradation at the high signal to noise ratio required for low BER. The received signal contains the coherent superposition of all transmitted waveforms. After applying the despreading CDMA filter, the received signal contains the desired ultrashort pulse (where propagation effects on the pulse envelope are neglected) and the interference component from all other users. Assuming the conversion process performs a linear mapping between the time and space domains, the generated spatial wave is proportional to the temporal signal. Since the detection device senses the intensity distribution, the process implements a non-coherent detection scheme on the ultrafast signal. The transmission time and carrier phase for each user is a random variable, since the network is operated asynchronously. Let the transmission times be uniformly distributed on $(-T_s/2,\ T_s/2)$, where T_s is the symbol period (since the network is operated asynchronously), and carrier phase is uniformly distributed on $(0,\ 2\pi)$. The random transmission time contains the effect of the additional delay due to PPM. Conditioned on knowledge of the transmission time and phase of all users, the interference is nonstationary complex Gaussian. However, the variances at each time slot, which are determined by the transmission times, are correlated since they are generated by the finite duration CDMA encoded waveforms of each user. Two adjacent slots will have nearly identical variances, while two slots that are farther apart are likely to have different variances, due to the finite temporal profile of the interference. The finite duration span of an encoded waveform implies that only a subset of the interfering users contribute to the error analysis, with the number of contributing users depending on the transmission times being in $(-1/\Omega,\ 1/\Omega)$. Therefore, the BER can be calculated as follows: the pair-wise probability of error is calculated (error between the desired slot to another one $r\cdot T_{ps}$ apart, where r is an integer), the expectation over the possible transmission times and phases of all users is calculated, and the union bound is applied for the error probability with M detection slots. The use of the union bound will generate slightly pessimistic BER values, however the result is rather tight for small M.

Performance curves of the hybrid PPM/ULP-CDMA format are shown in Figure 2, using 200 fs Gaussian profile pulses and different spectral chip bandwidths. From the results, it is clearly seen that the aggregate throughput of the PPM/CDMA system is much higher than that of the OOK/CDMA system, and that the performance of the proposed system gets better as the effective number of chips, N_{eff}, increases. It is also seen that the bandwidth efficiency of the proposed system gets better as M increases. Figure 3 compares the performance of 100 and 200 fs pulses for various spectral chip bandwidths when M=32. It can be seen that the performance of the proposed system improves by reducing the pulse duration τ (effectively increasing the bandwidth support of the pulse) while the spectral chip bandwidth remains constant (therefore, the effective number of chips increases). It is also seen that the performance of the proposed system can be improved by reducing τ while the effective number of chips remains constant (therefore, the spectral chip bandwidth increases). This is also primarily due to the enlarged bandwidth. It indicates that for fixed effective number of chips (achieved with smaller τ and larger Ω, such

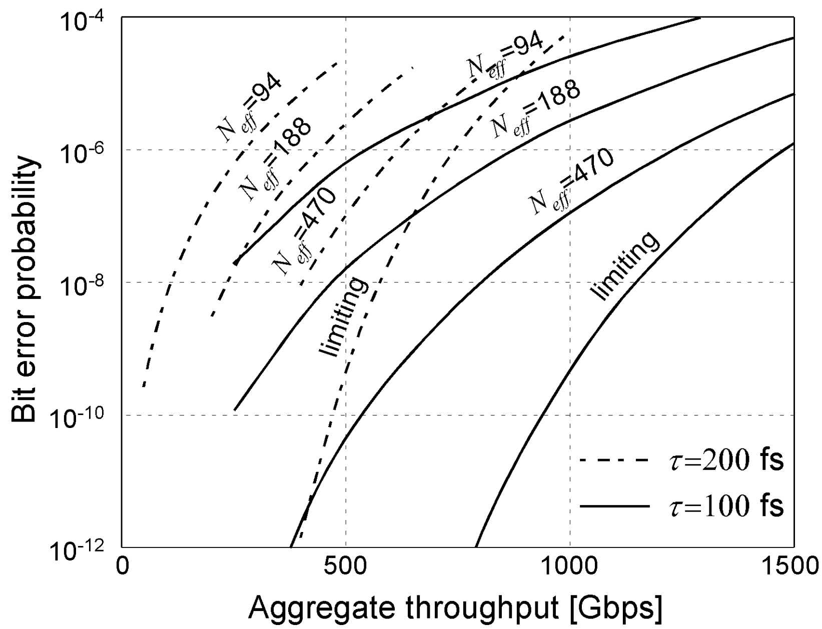

Figure 3: BER comparison for 100 and 200 fs pulses and dependence on spectral chip bandwidth. Symbol period is 10 ns. Limiting curves are for large N_{eff} by invoking the central limit theorem.

that $\tau\Omega$ is constant), yields better performance because the duration of an interfering signal is reduced with the same peak power reduction.

The strong dependence of the BER on N_{eff} for fixed pulse duration is due to the impulsive nature of the probability density function (PDF) due to the nonstationarity of the interference. As N_{eff} is increased, the encoded waveforms' duration increases (~$1/\Omega$) as does the probability that an interferer indeed interferes (~$1/\Omega T_s$). This reduces the impulsive nature of the PDF, and in the limit of very large N_{eff} implies that the interference can be modeled as a stationary complex Gaussian process. The stationary variance is found by invoking the central limit theorem, yielding $\sigma^2 = P_0/N_{eff} \cdot (J-1)/(\Omega T_s)$, where P_0 is the peak power of the ULP and J is the total number of users. The variance simply reflects that it is comprised from J–1 interferers, where the energy of a single interferer is distributed over T_s. The performance obtained by the Gaussian PDF approximation is the maximum achievable. Using the stationary Gaussian approximation for the performance bound, a few more important system characterization parameters can be defined. Let the SNR per symbol be defined as $\gamma_s = P_0/\sigma^2 = N_{eff}\Omega T_s/(J-1)$ and using the union bound for the BER of M-ary orthogonal modulation with noncoherent reception in an additive white noise channel (probability of error $P_e = M/4 \cdot \exp(-\gamma_s/2)$), the number of users as a function of the desired error rate and system parameters can be found. By defining the aggregate throughput of the system $\kappa = J \cdot \log_2(M)/T_s$ (bits per symbol time times the number of users), the maximum throughput as a function of the desired error rate is characterized as

$$\kappa_{\max} = \frac{N_{eff}\Omega \log_2(M)/2}{\ln(M) - \ln(4P_e)} \tag{1}$$

Similarly, the bandwidth efficiency, β, of the PPM/CDMA technique can be derived by dividing the throughput by the bandwidth of the employed ultrashort pulses. Using the Gaussian pulse envelope model for determining N_{eff}, the maximum aggregate throughput and bandwidth efficiency can be expressed as

$$\kappa_{\max} = \frac{\sqrt{\ln(2)}}{\sqrt{\pi}\,\tau} \frac{\log_2(M)}{\ln(M) - \ln(4P_e)} \tag{2}$$

and

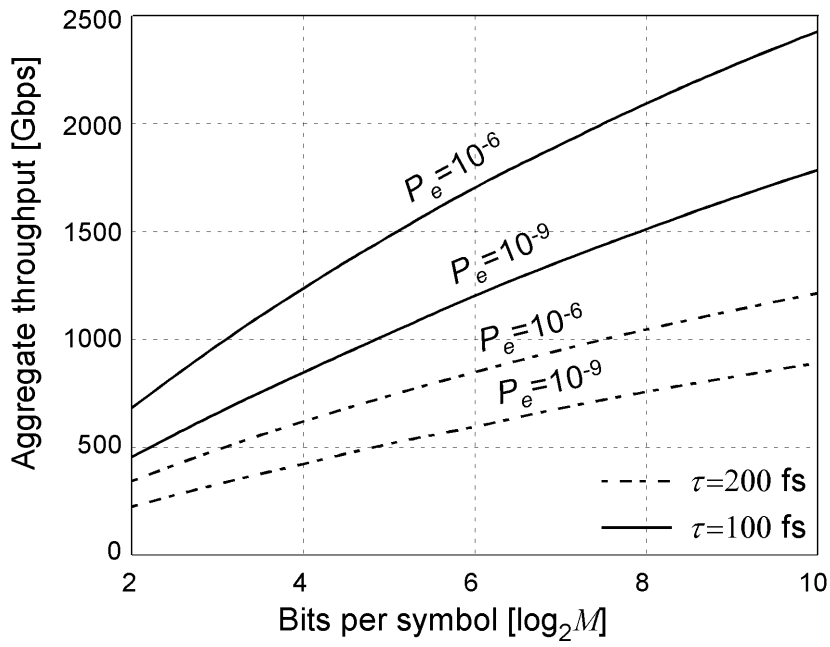

Figure 4: Limiting aggregate throughput of PPM/CDMA format for P_e=10^{-6} and 10^{-9} with 100 and 200 fs pulses as a function of the encoded bits per transmitted pulse.

$$\beta_{\max} = \frac{\sqrt{\pi}}{2\sqrt{\ln(2)}} \frac{\log_2(M)}{\ln(M) - \ln(4P_e)} \tag{3}$$

Using a 100 fs Gaussian pulse with M=32 and P_e=10^{-6}, it is found that $\kappa_{\max}$=1.48 Tbps and $\beta_{\max}$=0.335 bps/Hz. Requiring P_e=10^{-9} reduces the performance to $\kappa_{\max}$=1.03 Tbps and $\beta_{\max}$=0.233 bps/Hz. The maximum achievable throughput, $\kappa_{\max}$, is plotted as a function of M in Figure 4, showing that the performance improves almost linearly by increasing M.

3. DISCUSSION

The performance of the PPM/CDMA does not fully exploit the system resources, since only a small fraction of the symbol period is utilized. The number of pulse positions that are considered is limited by the time window of the time-to-space converter. This time window (on the order of tens of ps) is much smaller than the symbol duration (ns scale), resulting in poor utilization of the available time, and consequently, the time-bandwidth product.

To improve the system performance, the detection time needs to be extended. One solution may be to increase the time window of the processor. However, this solution requires larger optical elements which is undesirable for realization and will decrease the conversion efficiency. An alternate solution is to detect several times with the time-to-space converter within the symbol duration. This can be performed by employing a bank of time-to-space processors, each with detection circuitry operating at the symbol rate. Alternatively, a single time-to-space processor can be used for detecting several times by supplying a sequence of reference pulses (spaced farther apart than the time window of the processor) and faster electronic circuitry.

The performance enhancement can be quickly estimated using the stationary Gaussian interference approximation. Since the detection range is extended, the possible pulse positions (and bits per pulse encoding) can be extended. Increasing M has been shown to greatly improve the system performance. A system cost concern will determine the optimal operating point, balancing the complexity associated with a greater detection range and the capacity improvement. A moderate approximation based on detecting 10% of the symbol time can lead to the following performance: Assuming T_s=10 ns, τ=100 fs, T_{ps}=200 fs, the number of pulse positions in a 1 ns range is 5000. Using M=4096 for estimating the performance and P_e=10^{-9}, the maximum aggregate throughput is 2.04 Tbps and bandwidth efficiency .462 bps/Hz. In the extreme case where almost the entire time range can be detected with the same parameters as above, it is possible to use M=2^{15}=32768, resulting in $\kappa_{\max}$=2.37 Tbps and $\beta_{\max}$=.537 bps/Hz. It is important to note that the above performance evaluation is based on Eqs. (2) and

(3), which were derived using the union bound for the *M*-ary detection. For such large values of *M* the tightness of the union bound deteriorates, with the actual performance achieving even better characteristics.

4. CONCLUSION

The combination of ULP-CDMA encoding for interference suppression in a broadcast network with PPM for an efficient data modulation scheme has been proposed for a networking application. The required functionality of the system requires the use of the spatial-temporal processors for shifting the pulse position at the transmitter and detecting the pulse position at the receiver. In comparison to other multi-access techniques, the BER performance is found to be interference limited. However, the CDMA format eliminates the need for synchronization, required in a TDM solution, or wavelength management, as in a WDM system. Such capacity tradeoff for access flexibility is common and justifiable in communication networks. Furthermore, the CDMA format is also less susceptible to propagation nonlinearities, as the encoded waveforms are spread out in time and their peak powers' reduced.

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