Optical CDMA for Internet Operation at Terabit Rates

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Optical networking: requirements and known solutions

**Desired system requirements:**
- Large information bandwidth per user
- Many supported communicating users
- Minimal system management

**WDM data networks:**
- Tunable lasers and/or receivers
- Wavelength assignment and control

**TDM data networks:**
- System synchronization
- Access management
Optical networking with ULP CDMA

Desired features:
- Short pulse communication for large capacity
- CDMA encoding for interference suppression
- Minimal system management

$H(\omega)$

Frequency domain

CDMA filter

Encoded

signal

Encoded signal

Encoded signal +

encoded interference

Time

filter

$H^*(\omega)$

Decoded signal +

interference

Spatial Fourier transform by a lens generates spatial dispersion

Grating diffraction generates angular dispersion

User $i$

User $j$

Shared network

Hybrid PPM/CDMA optical networking

**Proposed solution:**
- Short pulse communication for large capacity
- CDMA encoding for interference suppression
- Efficient data modulation (PPM)

**Transmitter**
- Ultrashort laser pulse source
- Data symbols
- Time delay generator
- Signal pulse at one out of $M$ possible locations
- CDMA encoder spectral filter

**Receiver**
- Detection circuitry
  - “Choose largest” logic
- Data symbols
- Detector array with $M$ detectors behind a mask
- **time-to-space converter**
- CDMA decoder spectral filter
- Ultrashort laser pulse source

**Broadcast**

**Added layer of sophistication:**
more complexity for greater performance
Femtosecond-rate time-to-space conversion

Spectral domain wave mixing of a signal waveform and a reference pulse:

Interaction of spectrally decomposed waves: \( Y(\omega) = \chi^{(2)}S(\omega)R(-\omega) \)

After spatial Fourier transform: \( y(x) \propto s(kx) \otimes r(-kx) \approx s(kx) \)

Output spatial signal  
Space domain representation of temporal signals  
Inverted reference spectrum  
Signal spectrum

Time-to-space: Principle of operation

- Wave mix inverted spectrally decomposed waves
- Generate monochromatic plane wave
- Image with spatial Fourier transform

Energy conservation: $\omega_{\text{low}} + \omega_{\text{high}} = \omega_{\text{high}}\omega_{\text{low}}$

Momentum conservation: Quasi-monochromatic

$\Delta t$ $\omega_{\text{low}}$ $\omega_{\text{high}}$ $\Delta x$
Femtosecond-rate space-to-time conversion

Interaction of spectral and spatial waves:

\[ Y(\omega) = (\chi^{(2)})^2 R(\omega) M(f_x) \]

After spatial Fourier transform:

\[ y(t) \propto r(t) \otimes m(kt) \approx m(kt) \]

Space-to-time: Principle of operation

Energy conservation:

\[ \omega_{\text{low}} + \omega_0 = \omega_{\text{high}} + \omega_0 \]

Momentum conservation:

\[ k_{\text{temp input}}(t) + k_{\text{spatial 1}} + k_{\text{spatial 2}} = k_{\text{temp output}}(t) \]

Instantaneous wavevector of temporal channel

spatial information bandwidth

conjugated plane wave from delta function

information imposed on instantaneous wavevector
Pulse packet generation and detection experiment

Real-time space-to-time conversion

Detected image by CCD

Real-time time-to-space conversion

Experiment: 0.8 μm center wavelength, 1 mJ combined energy, 100 fs pulse, free space propagation between transmitter and receiver
Typical parameters used in our evaluation:

\[
\begin{align*}
\tau &= 100 \text{ fs} \\
T_s &= 10 \text{ ns} \\
\Omega &= 25–100 \text{ GHz} \\
T_{ps} &= 100–200 \text{ fs} \\
N_{eff} &= 50–200 \\
M &= 4–64
\end{align*}
\]

- Ideally, desire large \( M \) for a large orthogonal alphabet size
- Ultrafast detection time window technology determines \( M \cdot T_{ps} \)
- Minimal \( T_{ps} \) is chosen, with limit determined by signaling orthogonality
PPM/CDMA performance analysis: 1

The received waveform, \( y(t) \), consists of the superposition of all the users’ encoded waveforms. Each user transmits with an independent time and phase.

\[
y(t | t_1, t_2, ..., t_J, \phi_1, \phi_2, ..., \phi_J) = \sum_{i=1}^{J} y_i (t | t_i, \phi_i)
\]

After the CDMA decoding filter and time-to-space conversion, the received waveform is converted to a spatial signal and its intensity detected, implementing a noncoherent detection scheme.

\[
R_x (x) \propto \left| p (t - X \cdot T_{PS}) + \sum_{i=2}^{J} y_i (t | t_i, \phi_i) \right|^2
\]

**Assumptions for analysis:**

Each user’s transmitted waveform is modeled as non-stationary, conditionally Gaussian (dependent on knowledge of transmission time and phase).

Expectation of transmitted waveform is zero and variance follows \( \text{sinc}^2(\cdot) \) profile.

Transmission times are uniformly distributed on \((-T_s/2, T_s/2)\).

Transmission phases are uniformly distributed on \((0, 2\pi)\).

Gaussian temporal pulse profile.

PPM/CDMA performance analysis: 2

**Solution technique:**

1. 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).
2. The expectation over the possible transmission times and phases of all users as a function of $r$ is calculated.
3. The union bound is applied for the error probability with $M$ detection slots.

When $\Omega$ decreases, encoded waveforms’ duration increases and process converges to stationary Gaussian case. Interference is “less bursty.”
PPM/CDMA performance curves

Using central limit theorem
Experiment: 0.93 µm center wavelength, 10 µJ energy, 200 fs pulse, 100 GHz spectral chip bandwidth, $N_{eff}=58$, PPM time shifts $T_{ps}=1.7$ ps.
A hybrid modulation scheme that combines CDMA encoding of ultrashort optical pulses with pulse position information encoding has been theoretically investigated and experimentally evaluated.

- The performance of the system improves with greater available pulse positions, smaller spectral chip bandwidths, and shorter laser pulses.
- PPM scheme provides a high bandwidth efficiency figure.
- Asynchronous network operation relieves management problems.
- Capacities exceeding 1 Tbps obtainable with today's components.