Optical CDMA for Internet Operation at Terabit Rates

Laurence B. Milstein, Yeshaiahu Fainman, Dan M. Marom, and Kwang Soon Kim

University of California, San Diego

Department of Electrical and Computer Engineering

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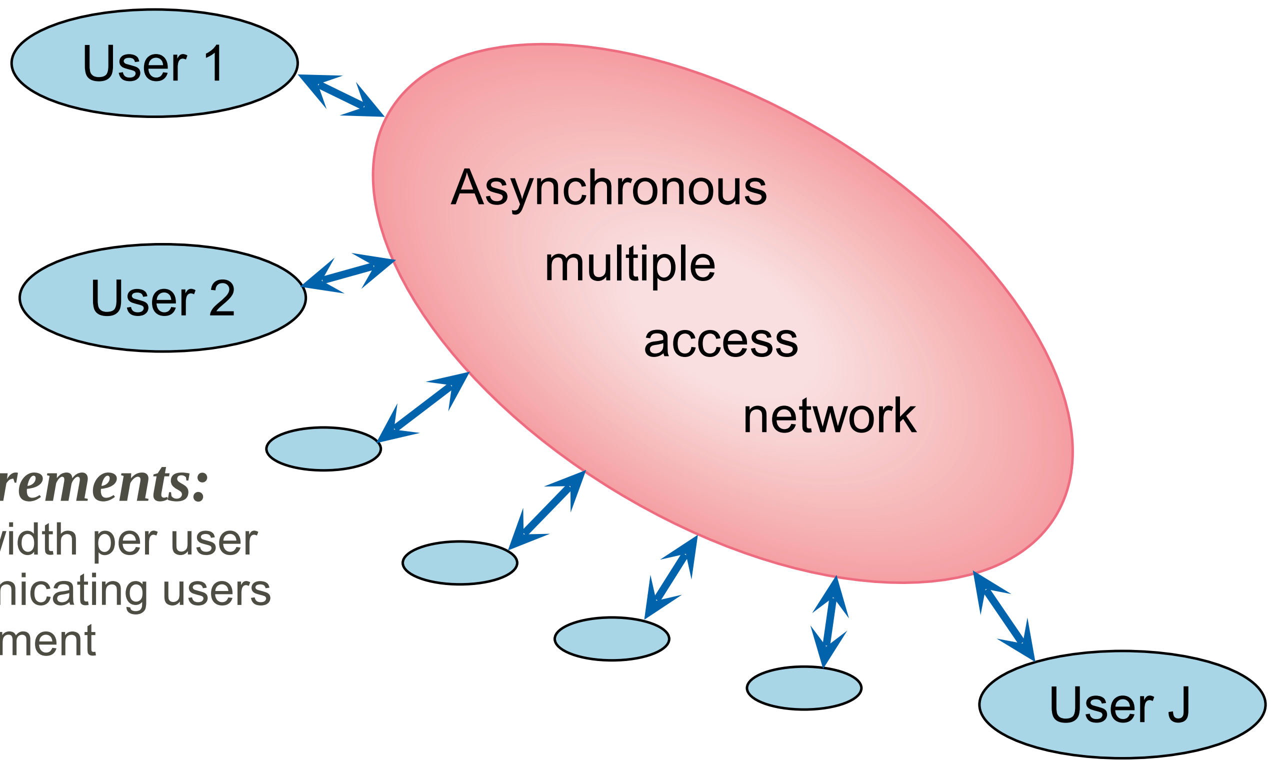
Optical networking: requirements and known solutions

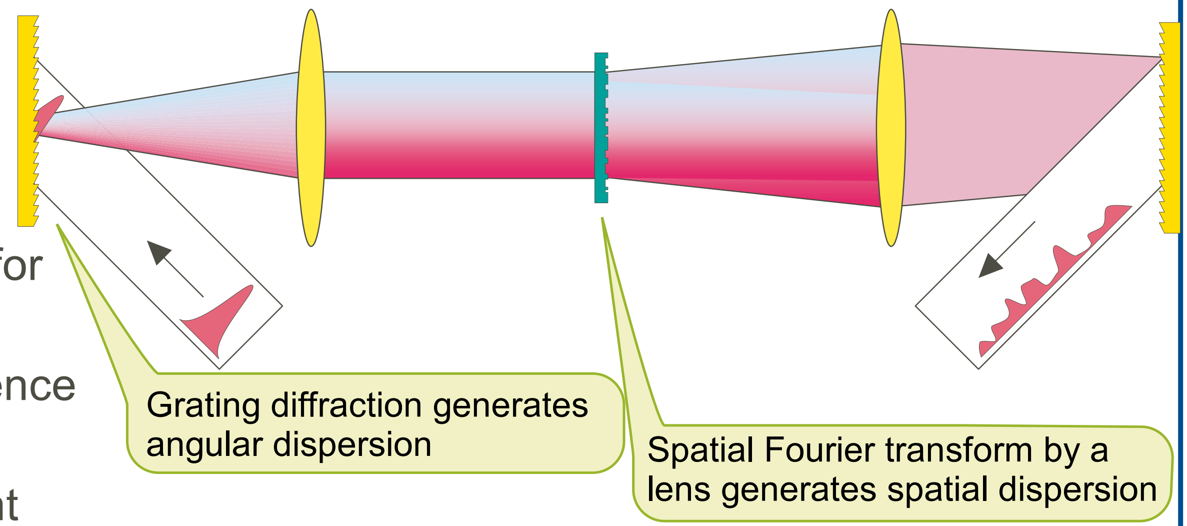


Desired system requirements:
- Large information bandwidth per user
- Many supported communicating users
- Minimal system management

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

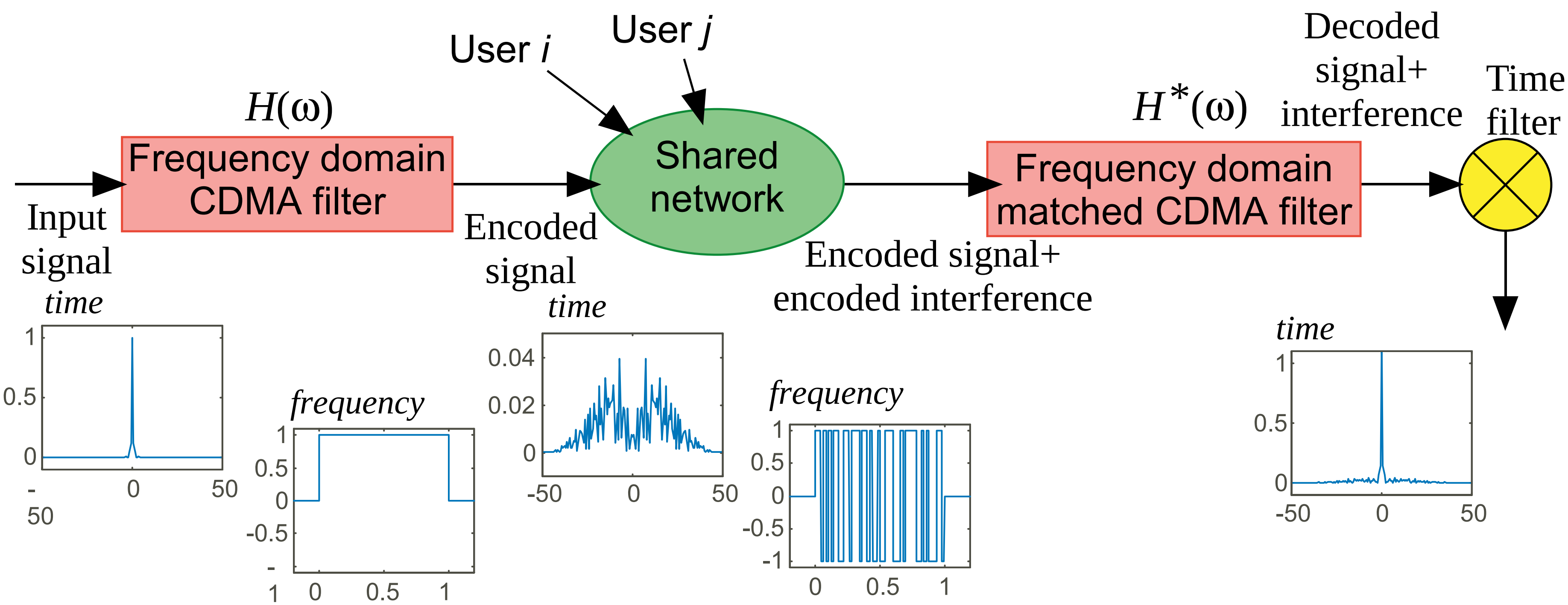
TDM data networks:
- System synchronization
- Access management

Optical networking with ULP CDMA



Desired features:

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



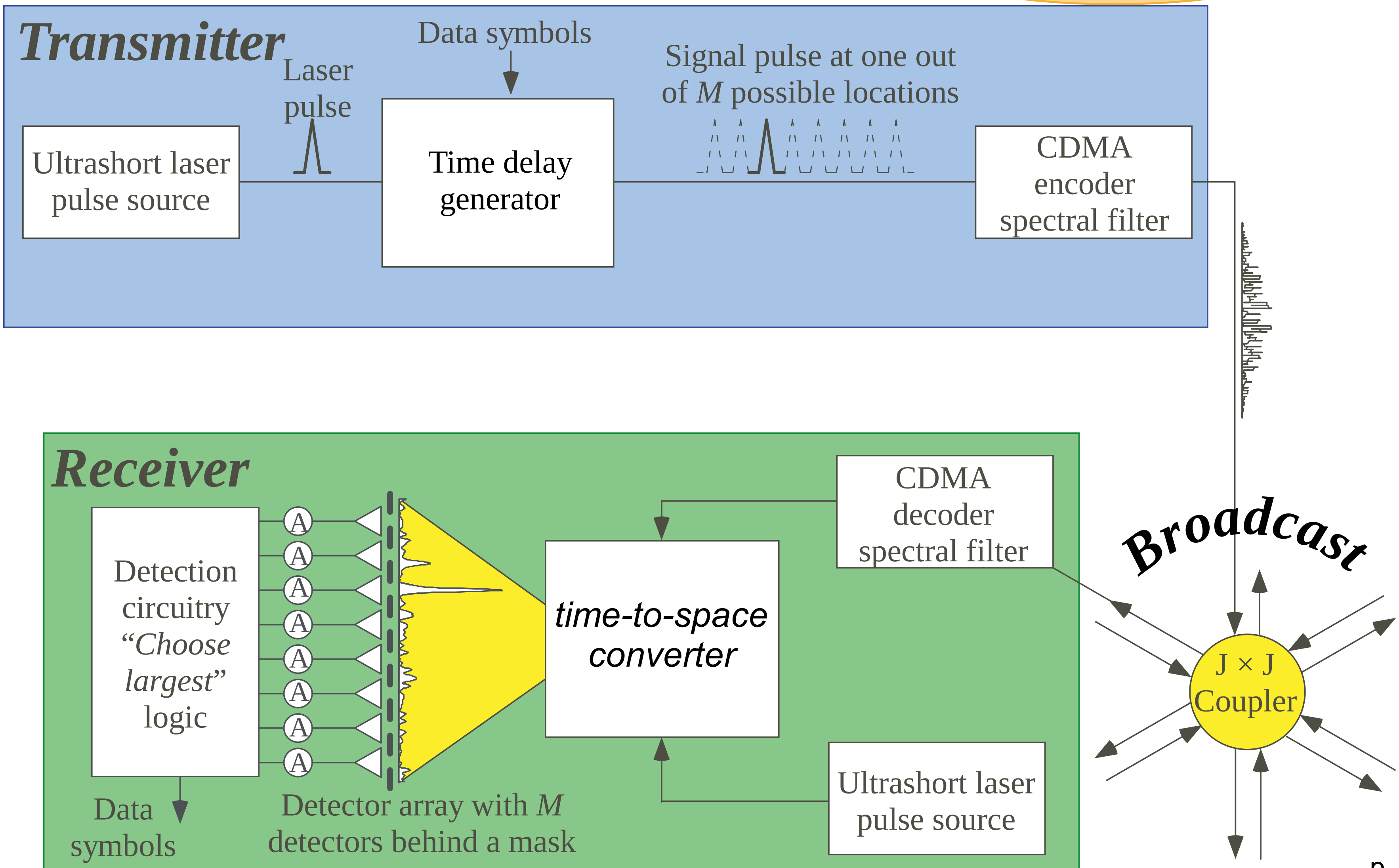
A. M. Weiner, J. P. Heritage, and J. A. Salehi, *Opt. Lett.* 13, 300-2 (1988).
J. A. Salehi, A. M. Weiner, and J. P. Heritage, *J. Lightwave Technol.* 8, 478-91 (1990).

Hybrid PPM/CDMA optical networking

Proposed solution:

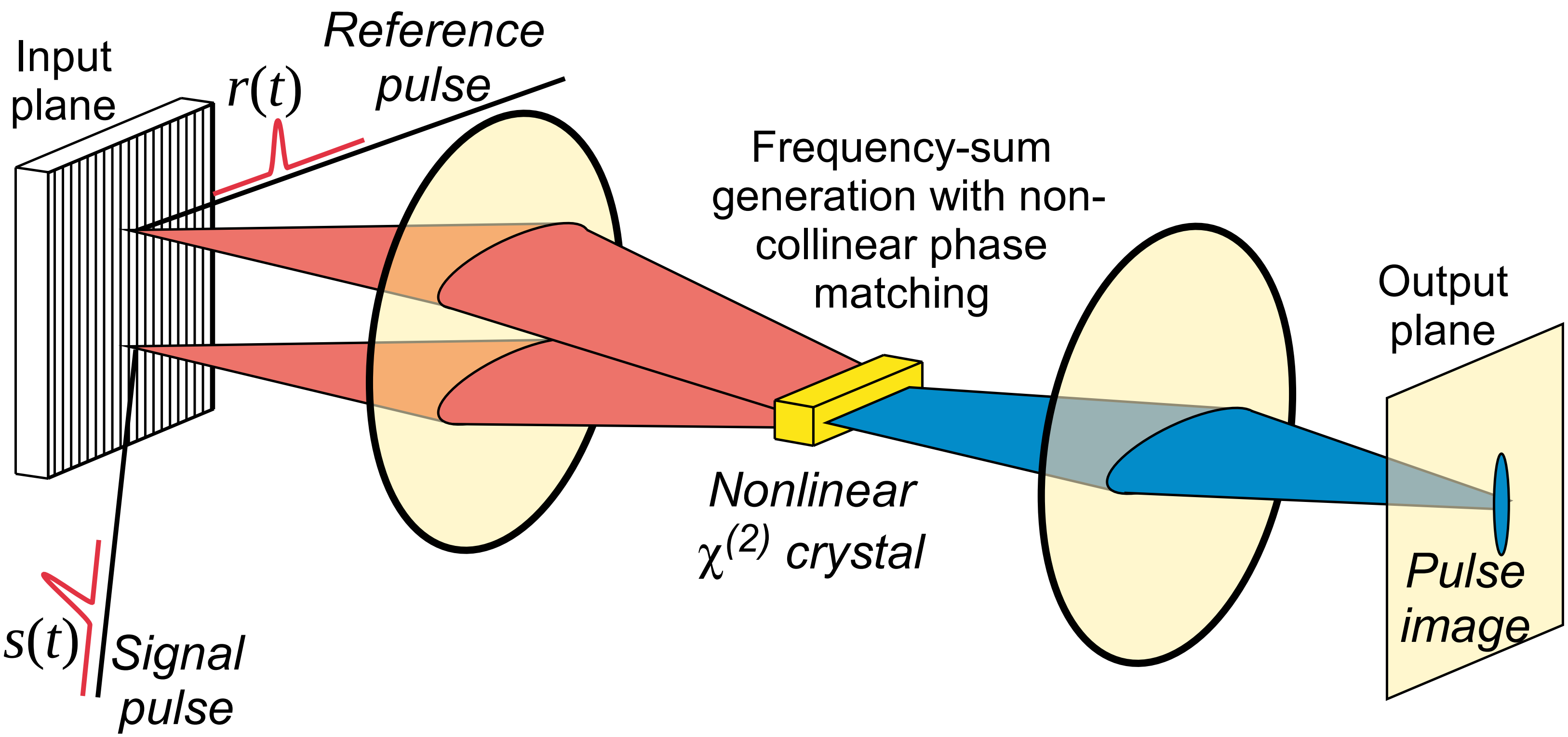
- Short pulse communication for large capacity
- CDMA encoding for interference suppression
- Efficient data modulation (PPM)

Added layer of sophistication: more complexity for greater performance



UCSD

Femtosecond-rate time-to-space conversion



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

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

Inverted reference spectrum

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

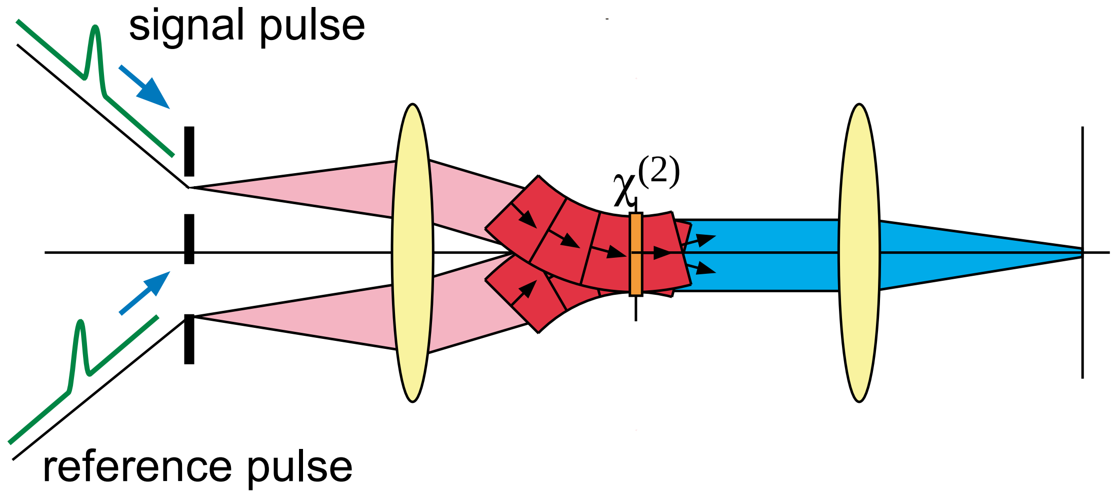
Signal spectrum

Output spatial signal

Space domain representation of temporal signals

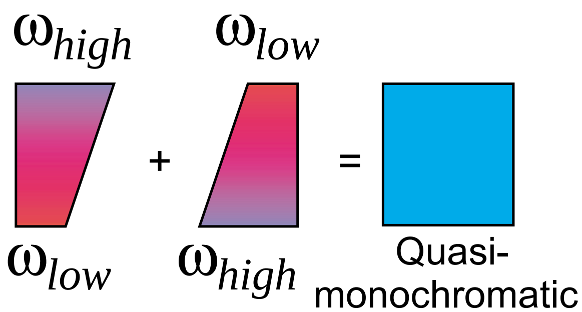
P. C. Sun, Y. T. Mazurenko, and Y. Fainman, *J. Opt. Soc. Am. A* 14, 1159-70 (1997).

Time-to-space: Principle of operation

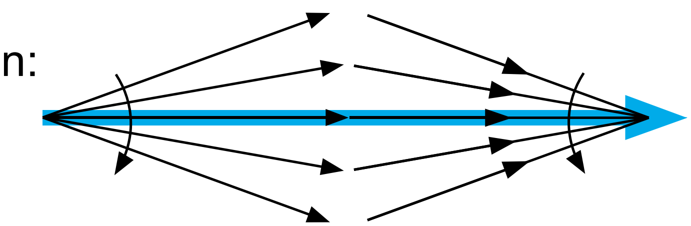


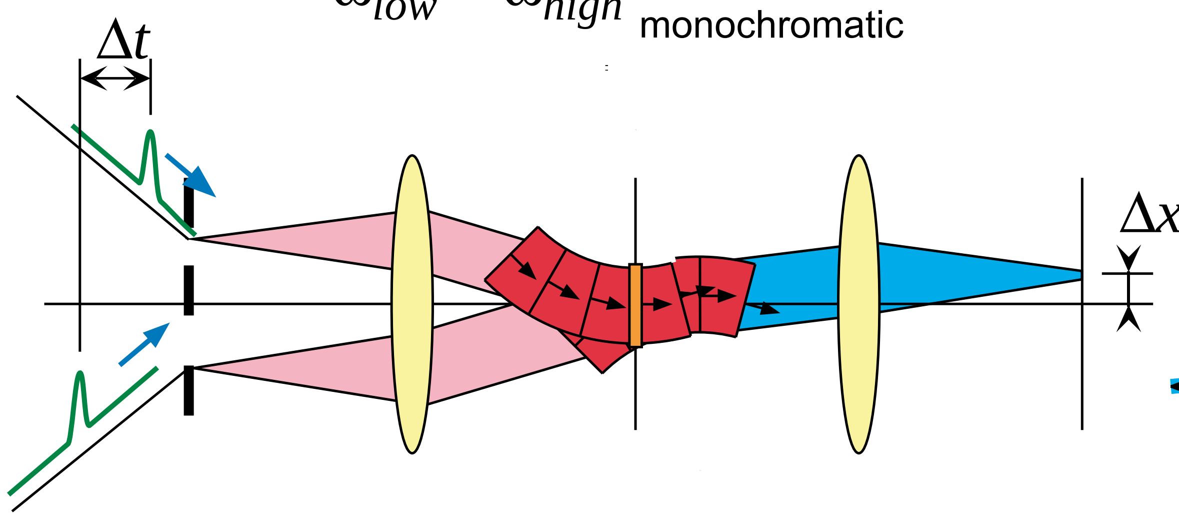
- Wave mix inverted spectrally decomposed waves
- Generate monochromatic plane wave
- Image with spatial Fourier transform

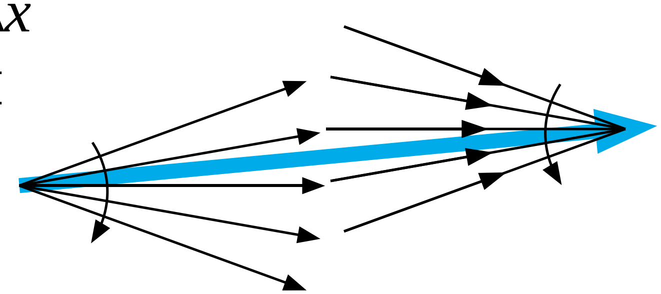
Energy conservation:



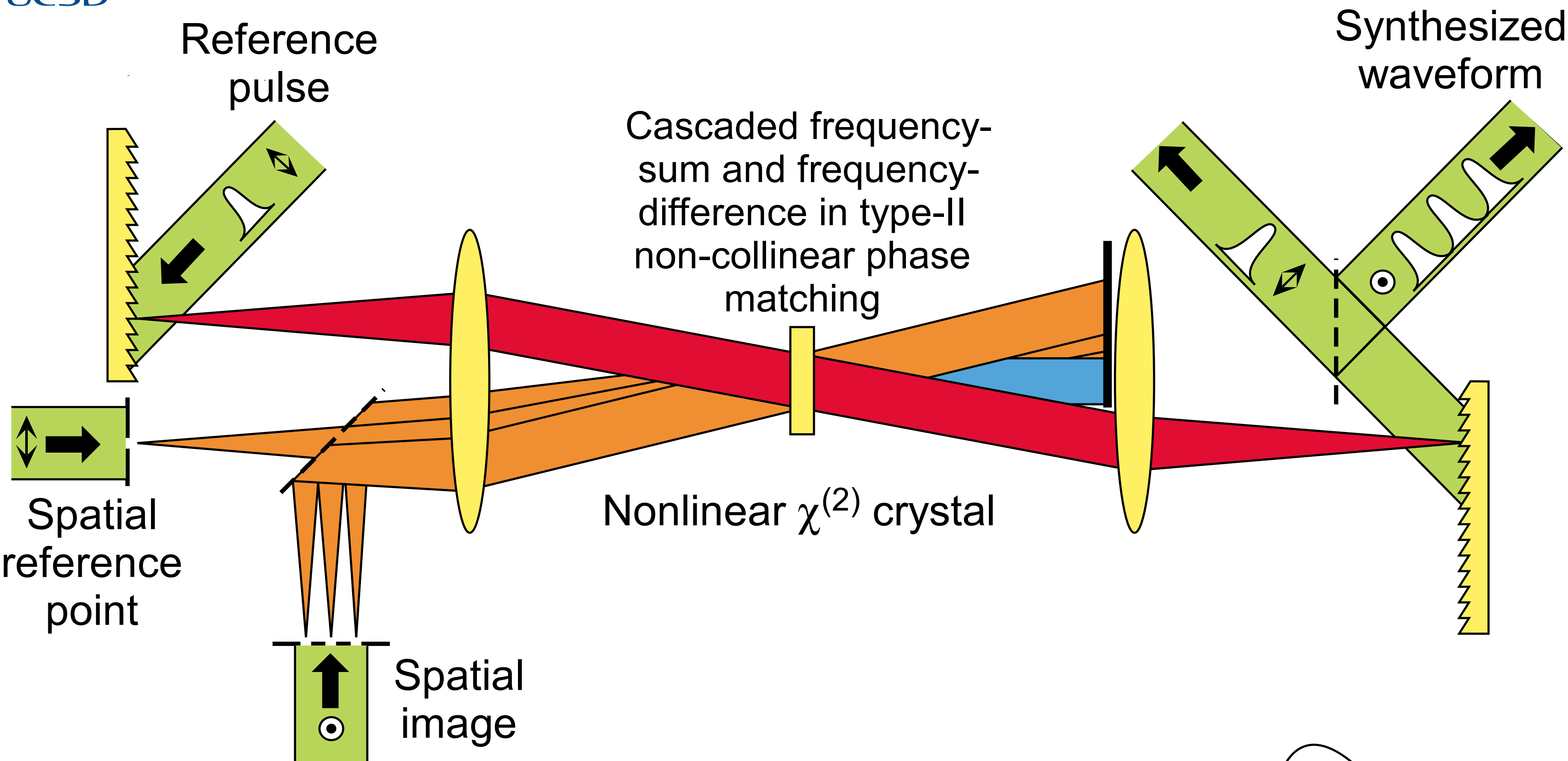
Momentum conservation:







Femtosecond-rate space-to-time conversion



Interaction of spectral and spatial waves: $Y(\omega) = (\chi^{(2)})^2 R(\omega) M(f_x)$

Spatial information

Pulse spectrum

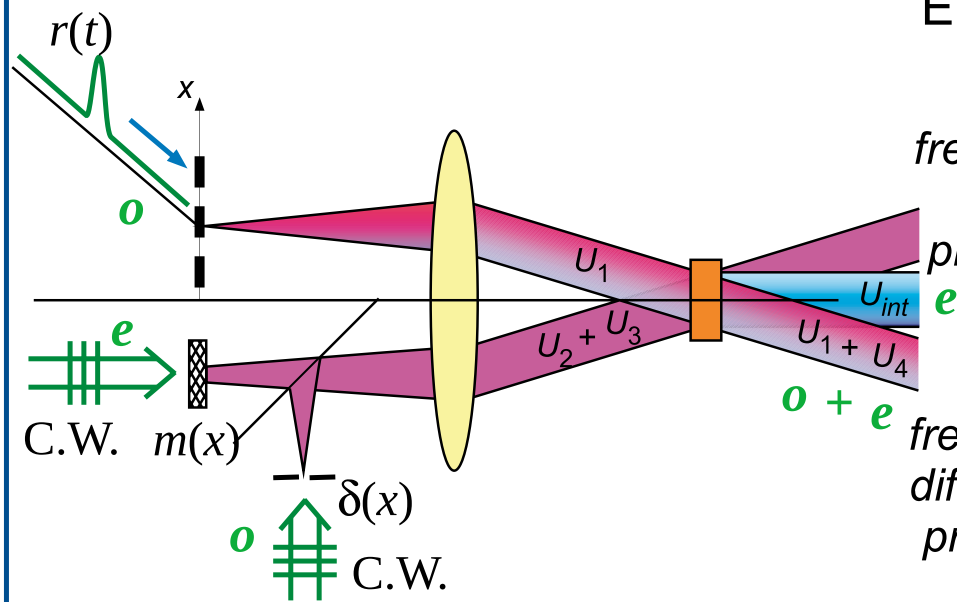
After spatial Fourier transform: $y(t) \propto r(t) \otimes m(kt) \approx m(kt)$

Output temporal signal

Time domain representation of spatial mask information

D. M. Marom, D. Panasenko, P.-C. Sun, and Y. Fainman, *Opt. Lett.* 24, 563-5 (1999).

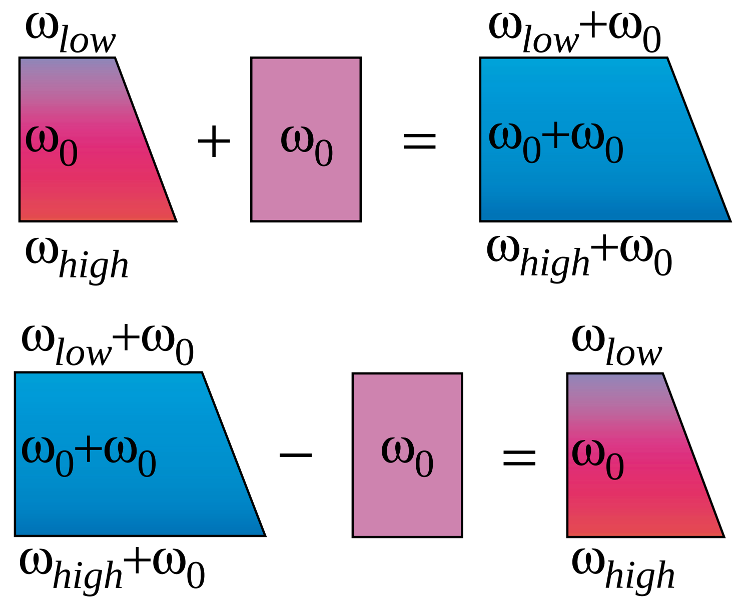
Space-to-time: Principle of operation



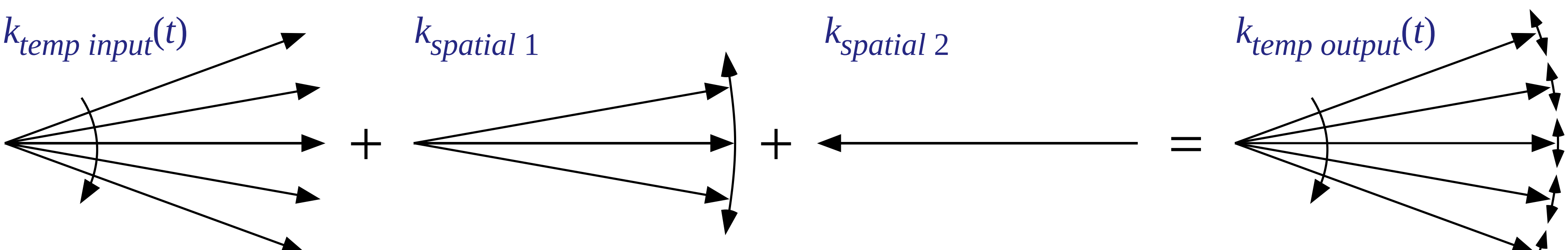
Energy conservation:

frequency sum process:

frequency difference process:



Momentum conservation:



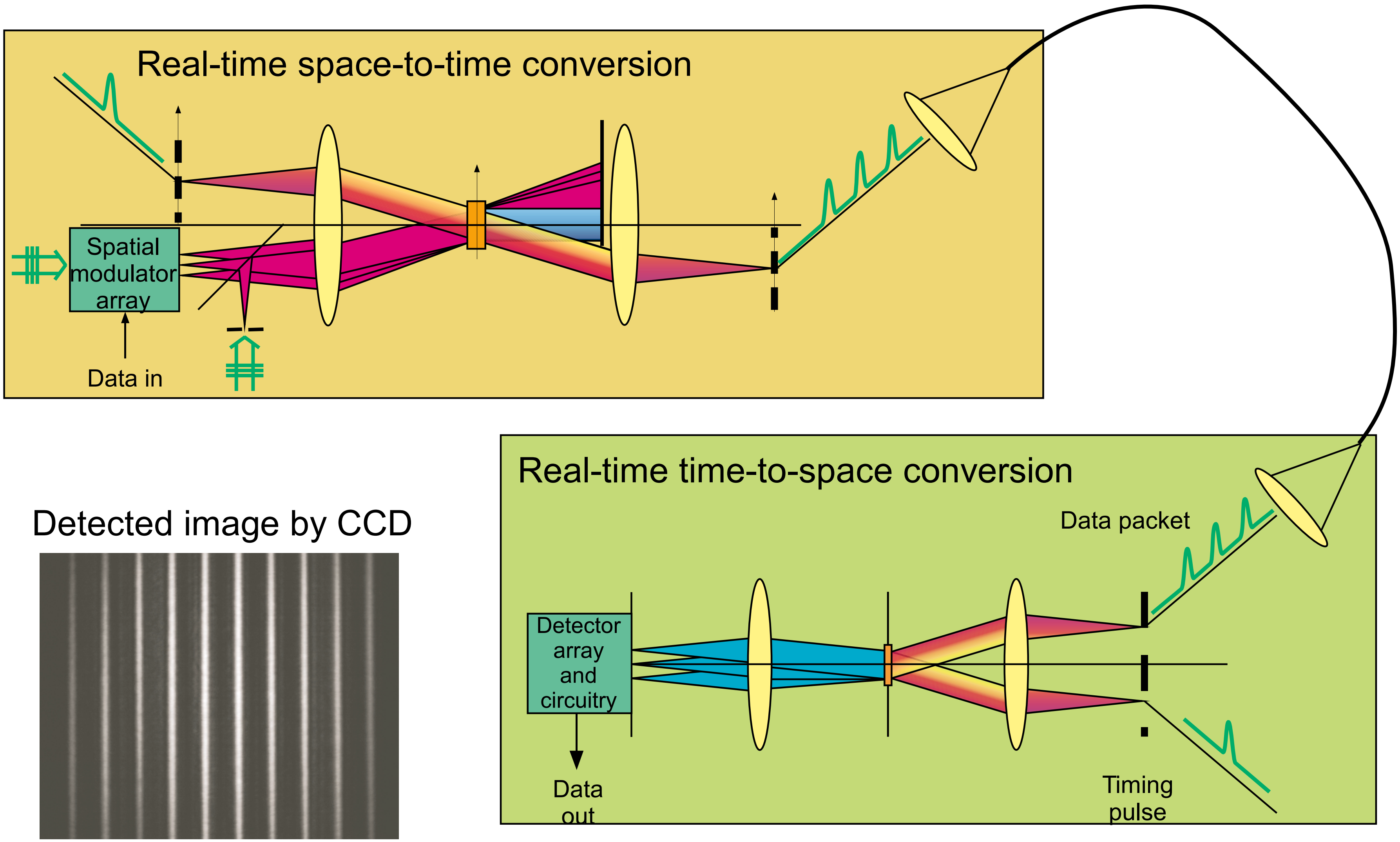
Instantaneous wavevector of temporal channel

spatial information bandwidth

conjugated plane wave from delta function

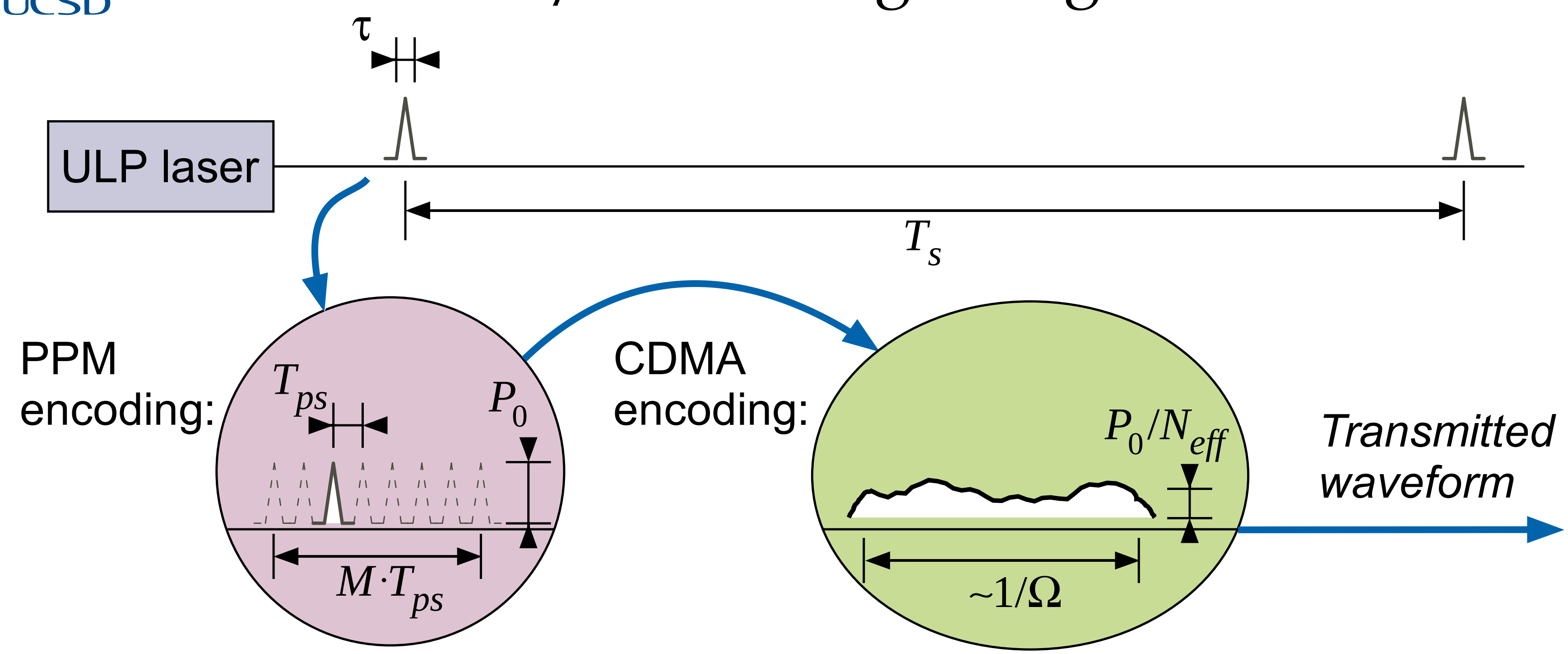
information imposed on instantaneous wavevector

Pulse packet generation and detection experiment



Experiment: 0.8 µm center wavelength, 1 mJ combined energy, 100 fs pulse, free space propagation between transmitter and receiver

PPM/CDMA signaling format



Typical parameters used in our evaluation:

$M \cdot T_{ps}$

τ=100 fs	T_s=10 ns
Ω=25–100 GHz	T_{ps}=100–200 fs
N_{eff}=50–200	M=4–64

- 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

UCSD

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

$$y\left(t \middle| t_1, t_2, \ldots, t_J, \phi_1, \phi_2, \ldots, \phi_J\right) = \sum_{i=1}^{J} y_i\left(t \middle| t_i, \phi_i\right)$$

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.

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

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 $\mathrm{sinc}^2(\bullet)$ profile.

Transmission times are uniformly distributed on $(-T_S/2, T_S/2)$.

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

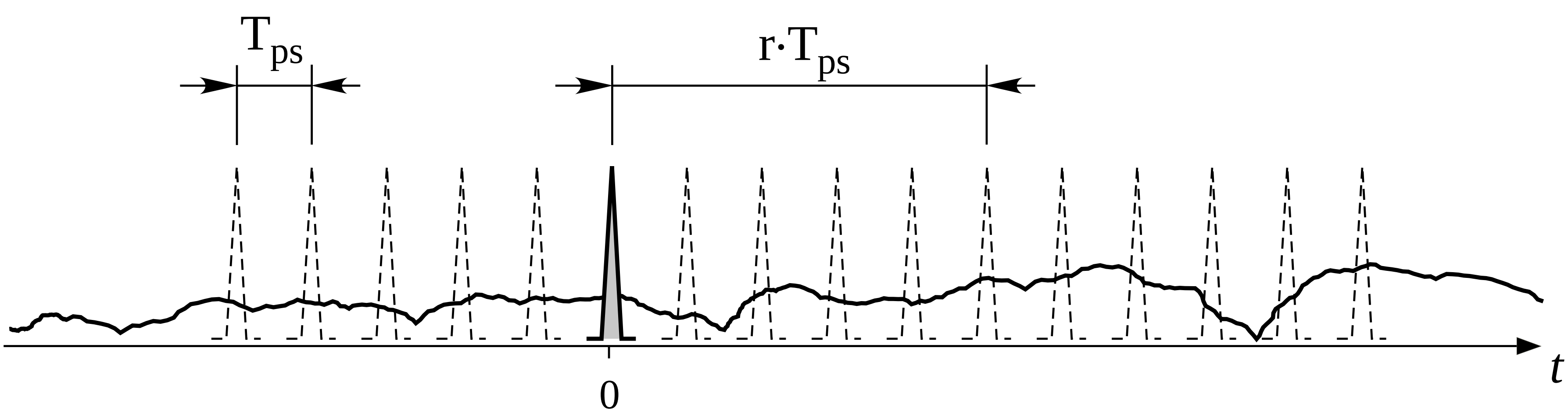
Gaussian temporal pulse profile.

K. S. Kim, D. M. Marom, L. B. Milstein, and Y. Fainman, submitted to *IEEE Trans. Commun.*

PPM/CDMA performance analysis: 2

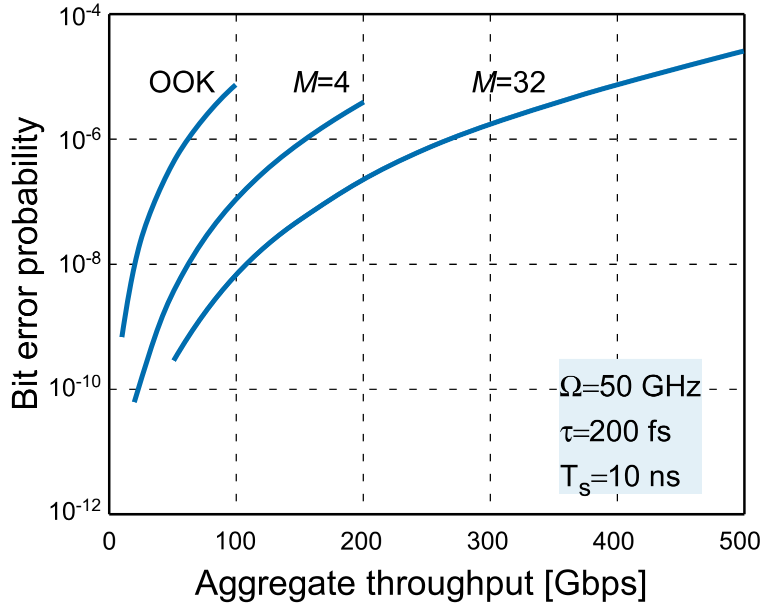
Solution technique:

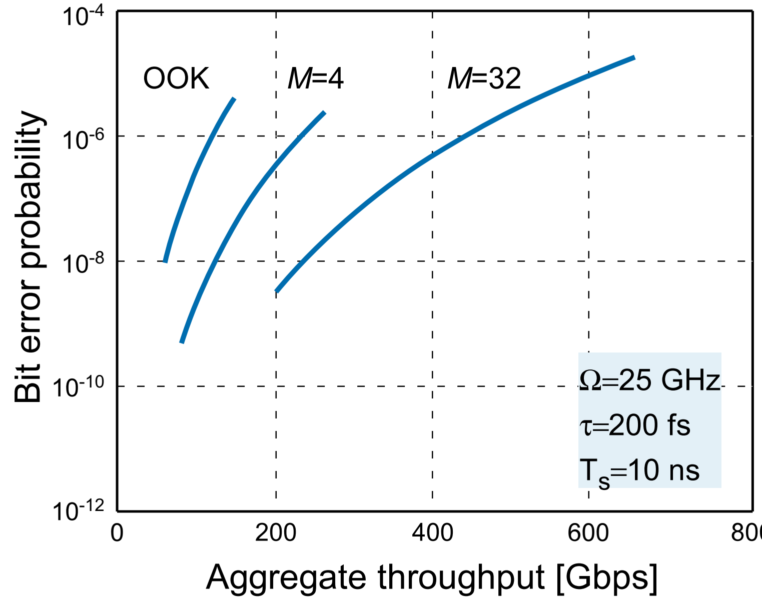
1. The pair-wise probability of error is calculated (error between the desired slot to another one $r \cdot T_{ps}$ apart, where r is an integer).
2. The expectation over the possible transmission times and phases of all users as a function of *r* is calculated.
3. The union bound is applied for the error probability with *M* detection slots.

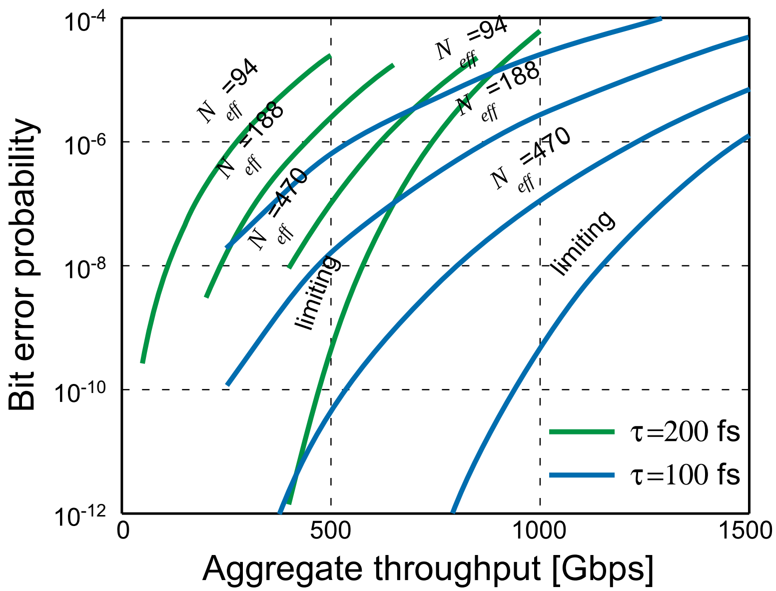


When Ω decreases, encoded waveforms' duration increases and process converges to stationary Gaussian case. Interference is "less bursty."

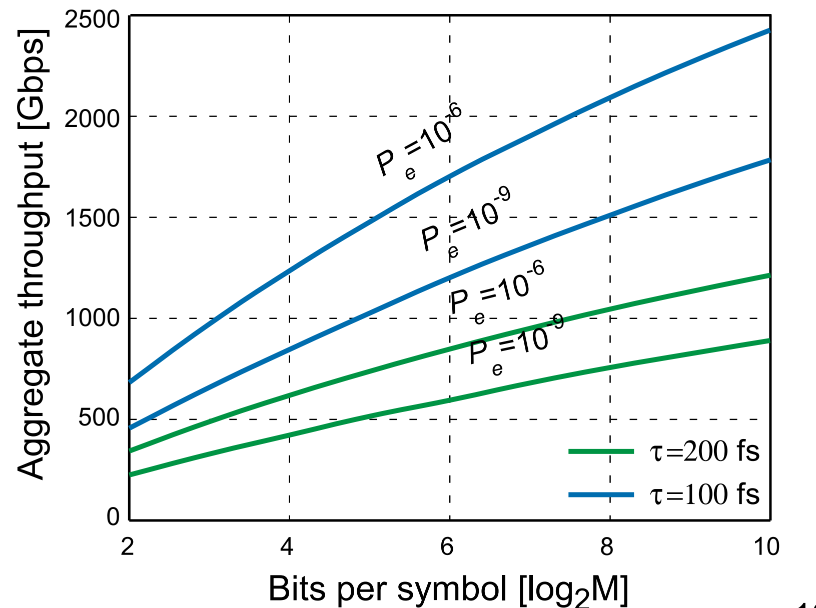
PPM/CDMA performance curves





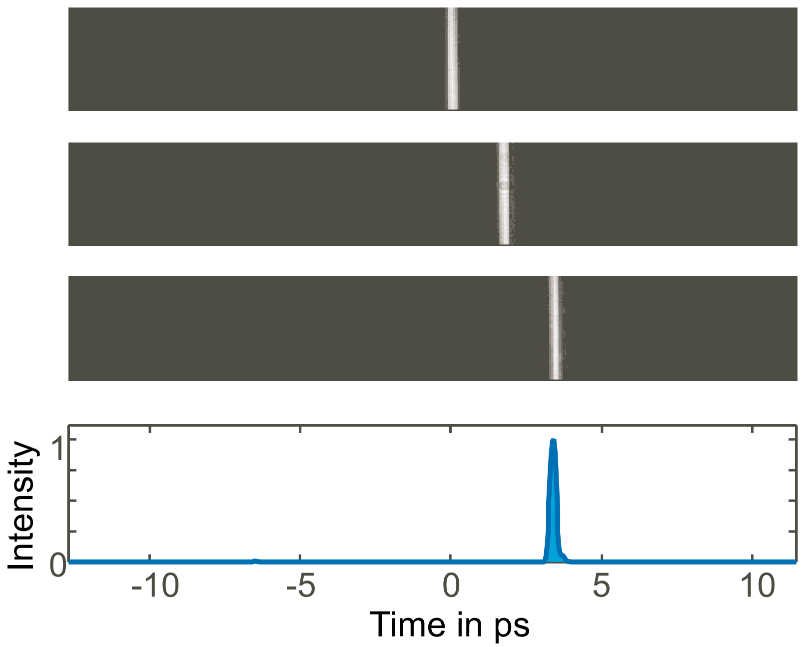


Using central limit theorem

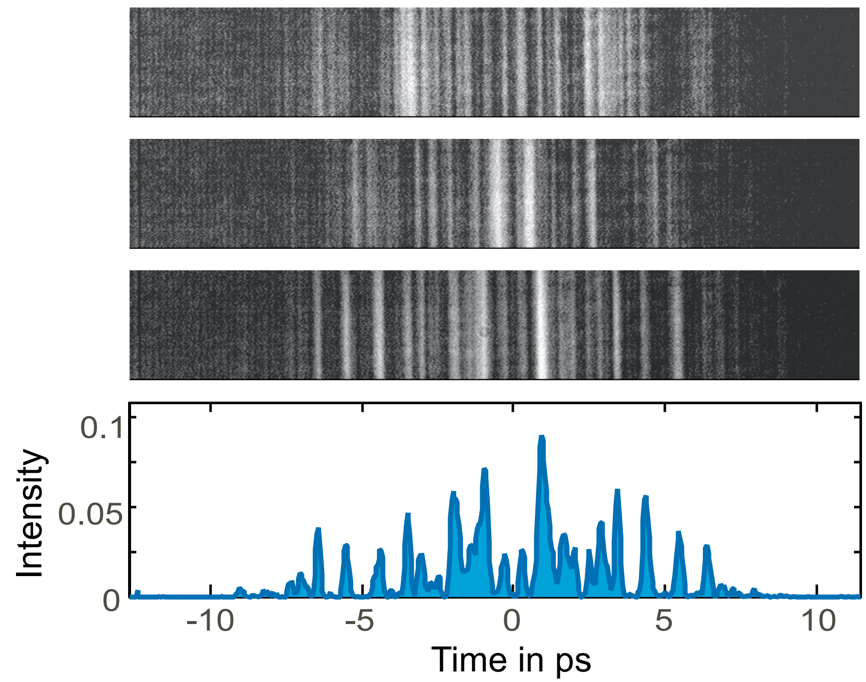


PPM/CDMA proof of concept

Encoding and decoding of ultrashort pulses with PPM data



Interference component from improperly decoded waveforms



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.

Conclusions

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.