Improving scalability and data security of incoherent OCDMA systems by employing ultrafast all-optical signal processing techniques

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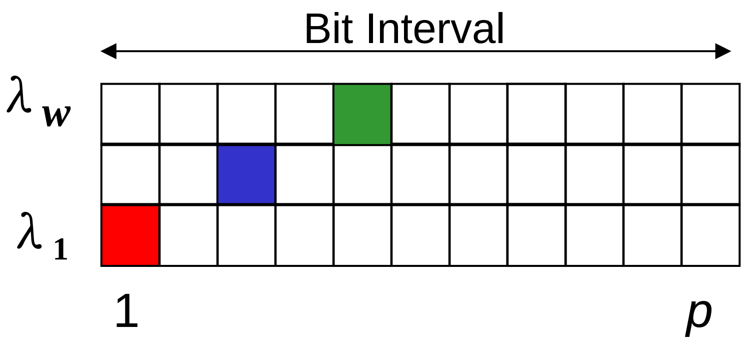
Outline

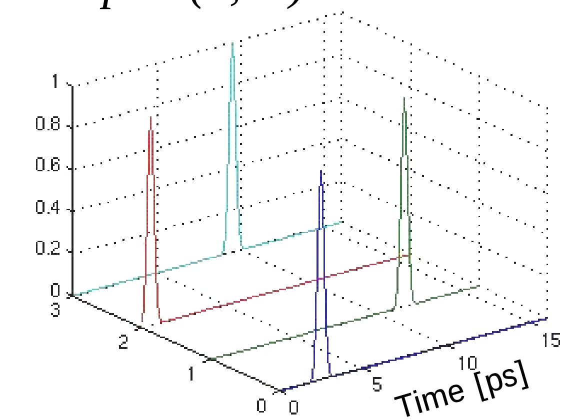
- Introduction
- Incoherent OCDMA
- Enhancing performance with all-optical signal processing
  - MAI suppression
  - Improving security
  - Improving system power budget
  - increasing number of simultaneous users
  - Increasing scalability and spectral efficiency with M-ary encoding
- Experimental results
- Conclusions

Incoherent OCDMA based on 2D prime codes

2D Wavelength-Hopping Time-Spreading Codes



Example: (4,11) 2D-WHTS



- Codes generated by simple one-line algorithm:

w = *weight: # of wavelengths*
p = *code length: # of chips*
i = *code number*

```
for   j = 0: w-1
code(i +1, j +1) = mod(j * i, p) +1
End
```

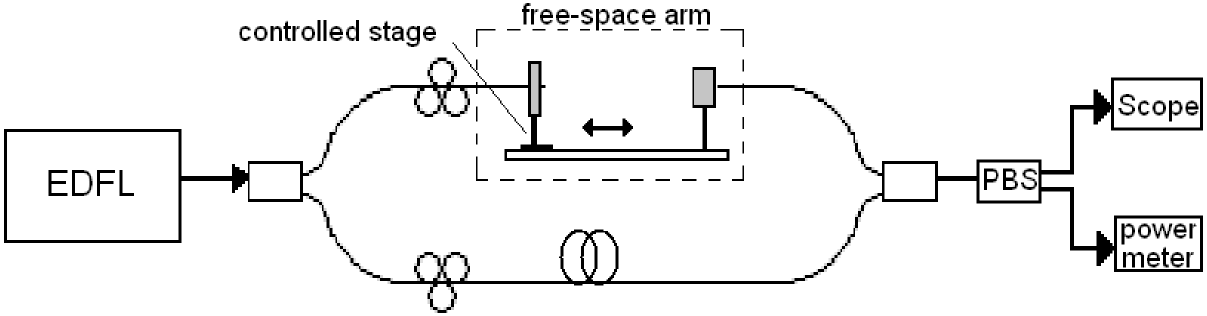
- Analytical expression for upper bound on BER
- The code scheme uses picosecond pulses at multiple wavelength to generate codes

multi wavelength low jitter picosecond laser is needed

Multiwavelength ps laser

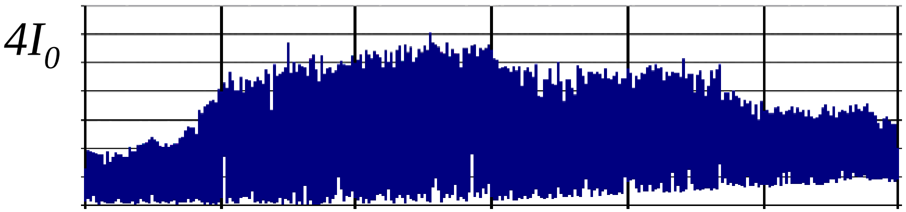
- 1.6 ps near transform-limited pulses efficiently utilize bandwidth
- Turn-key operation (< 40 fs timing jitter)
- High output power (15 dBm per wavelength)
- Low coherence

Experimental set up to study laser coherence



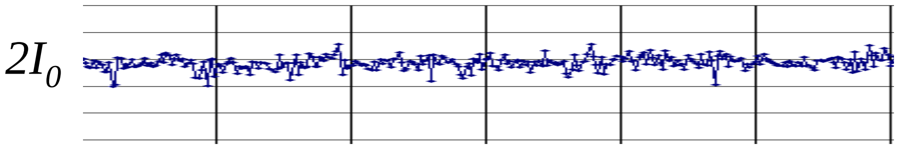
Interferometric equation: $I_{tot} = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\delta\phi)$

Experimental results:



"same" pulse interaction

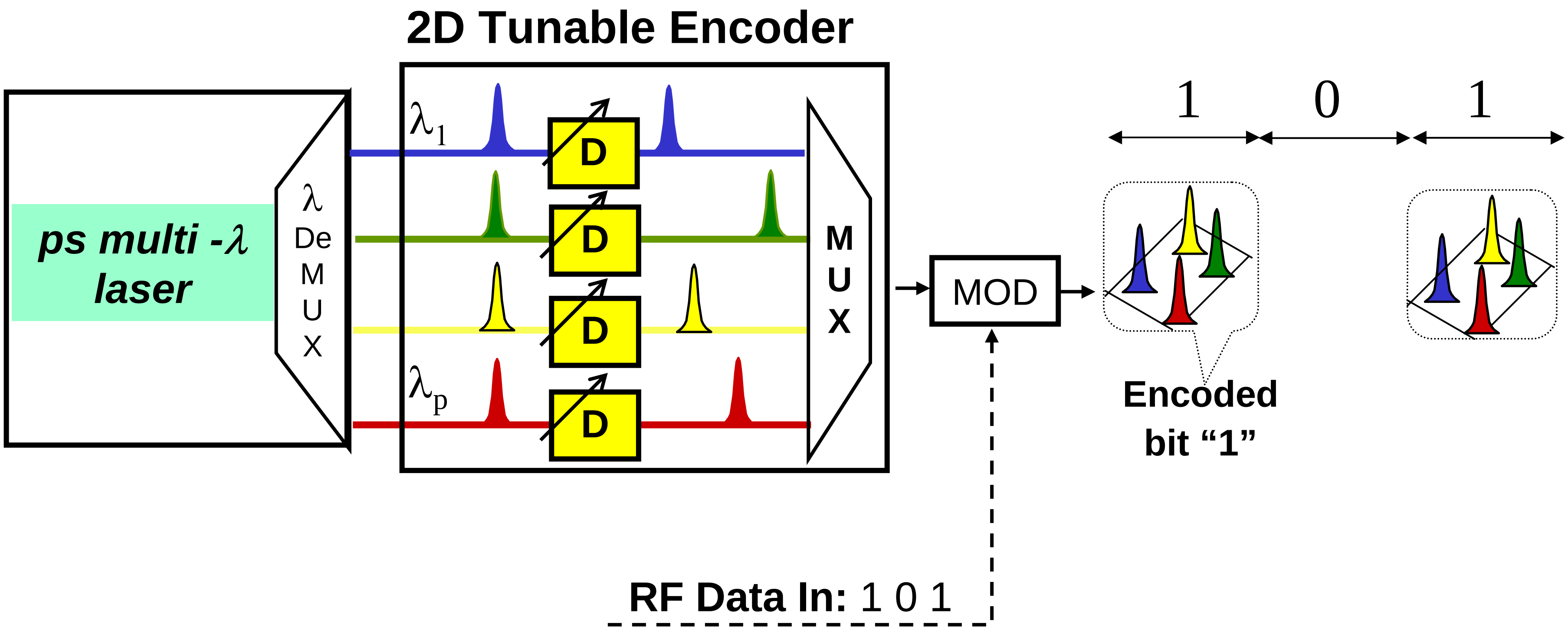
Pulse is coherent with "itself"



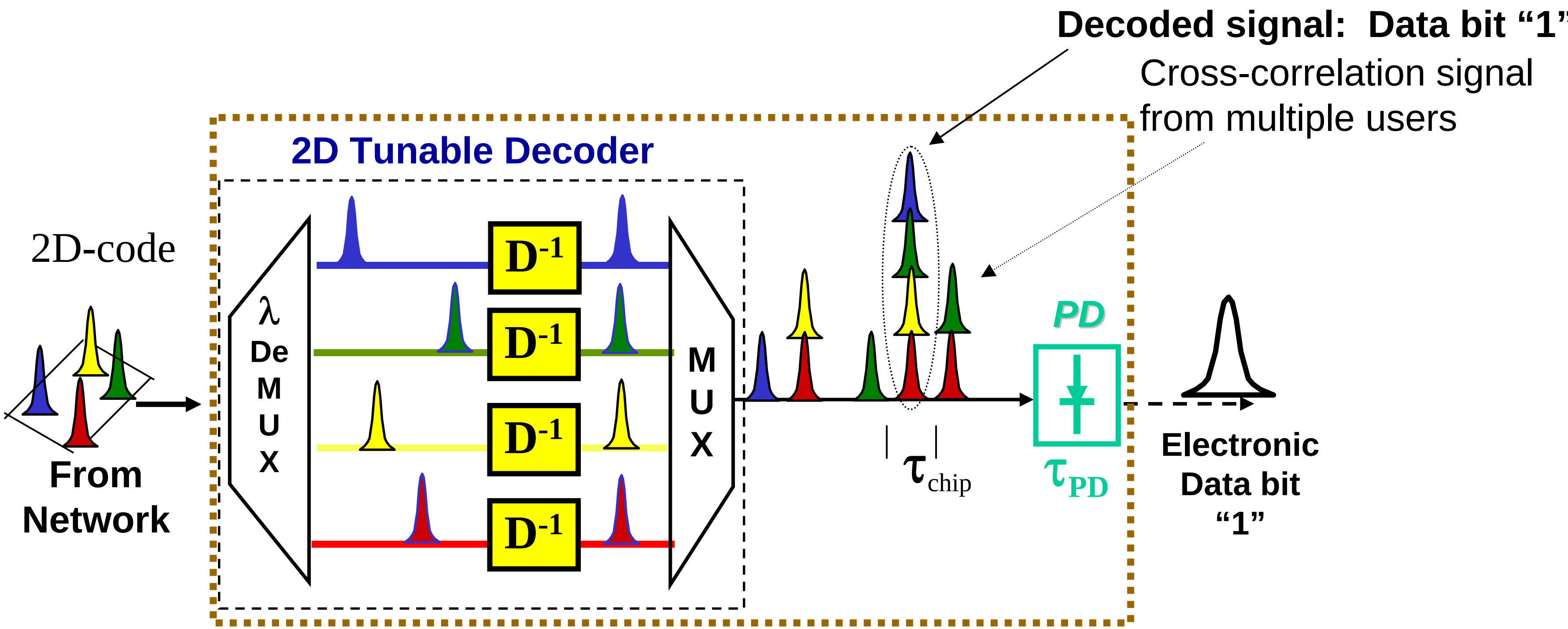
"pulse to pulse" separation

NO interference is observed

OCDMA Transmitter transmitting 2D-WHTS codes



Receiver diagram

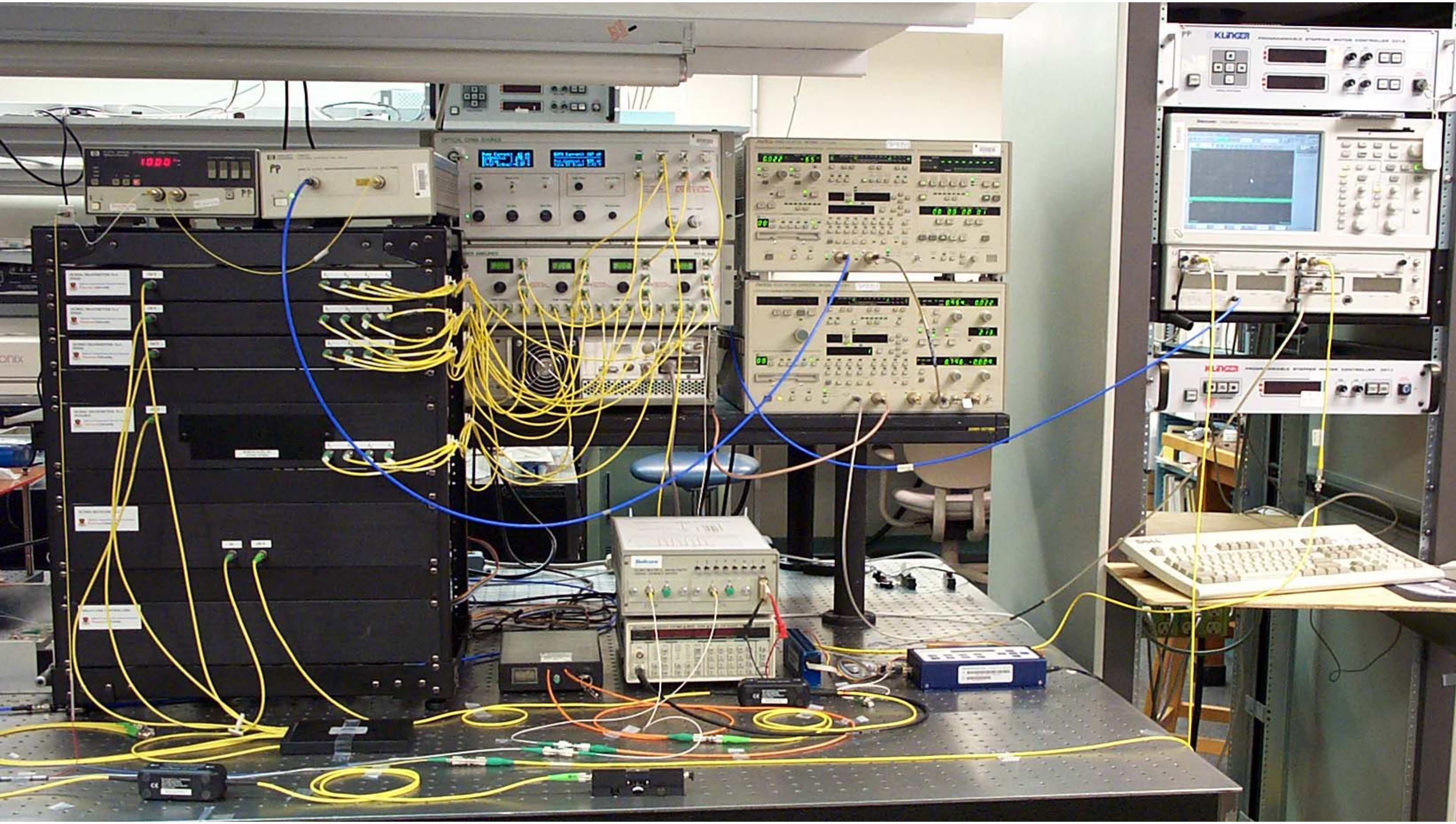


$\tau_{PD} < \tau_{chip}$

D = reconfigurable optical delay lines

D^{-1} = indicates "inverse" delay in reference to the delays D in the Transmitter

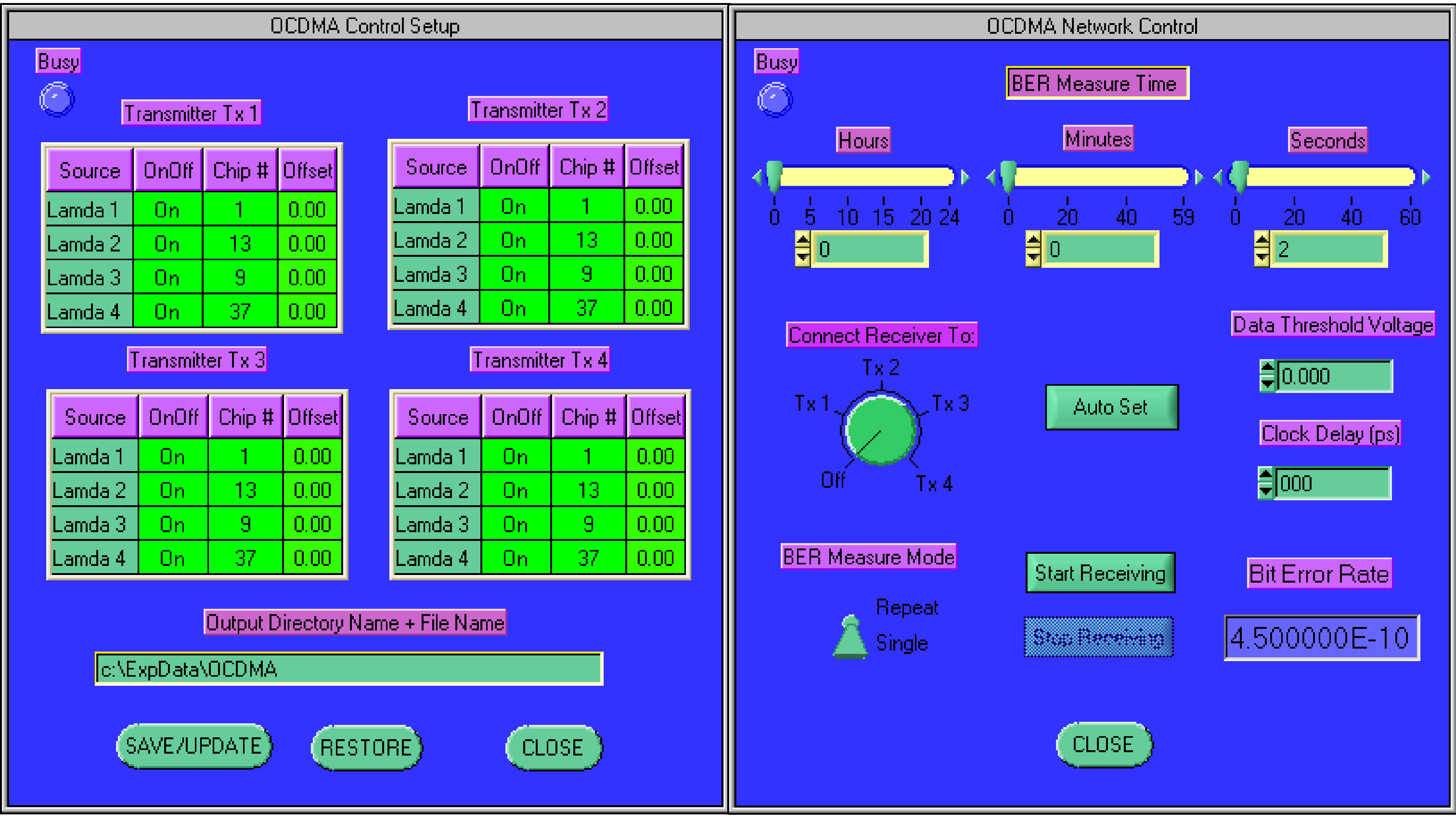
OC-48 OCDMA Princeton's Testbed



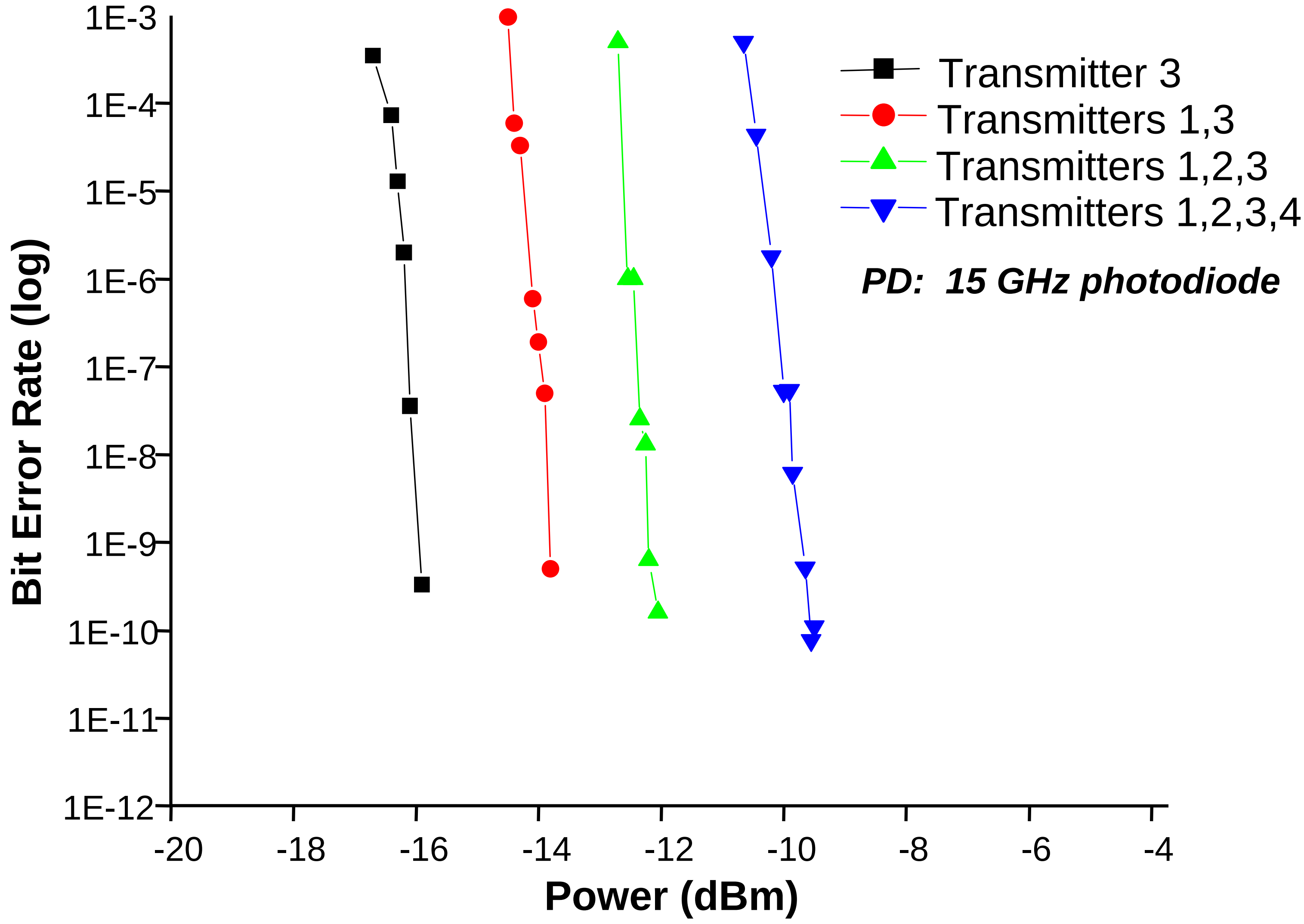
2D (4,101) WHTS codes
(4 wavelengths, 101 chips)

- **OC- 48 data rate**
- **4 Transmitters**
- **1 Tunable Receiver/Decoder**

Control Interface

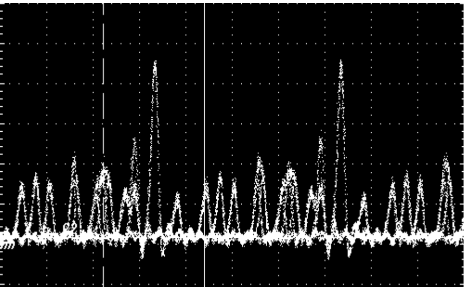


Performance – with 4 simultaneous users

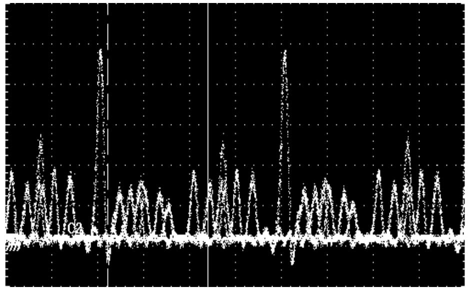


Multi access interference (MAI) penalty is evident

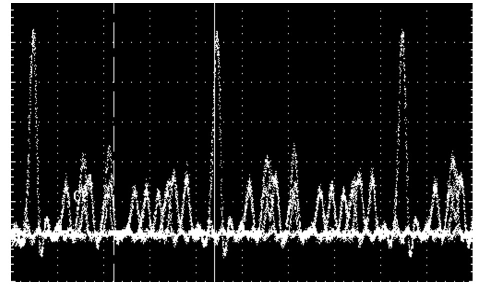
Performance of each user



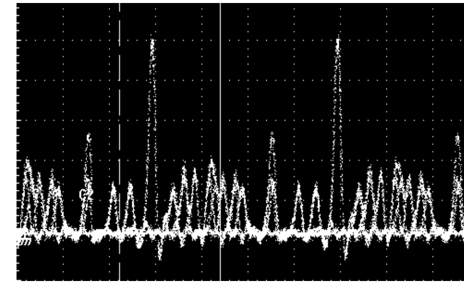
Transmitter 1



Transmitter 2

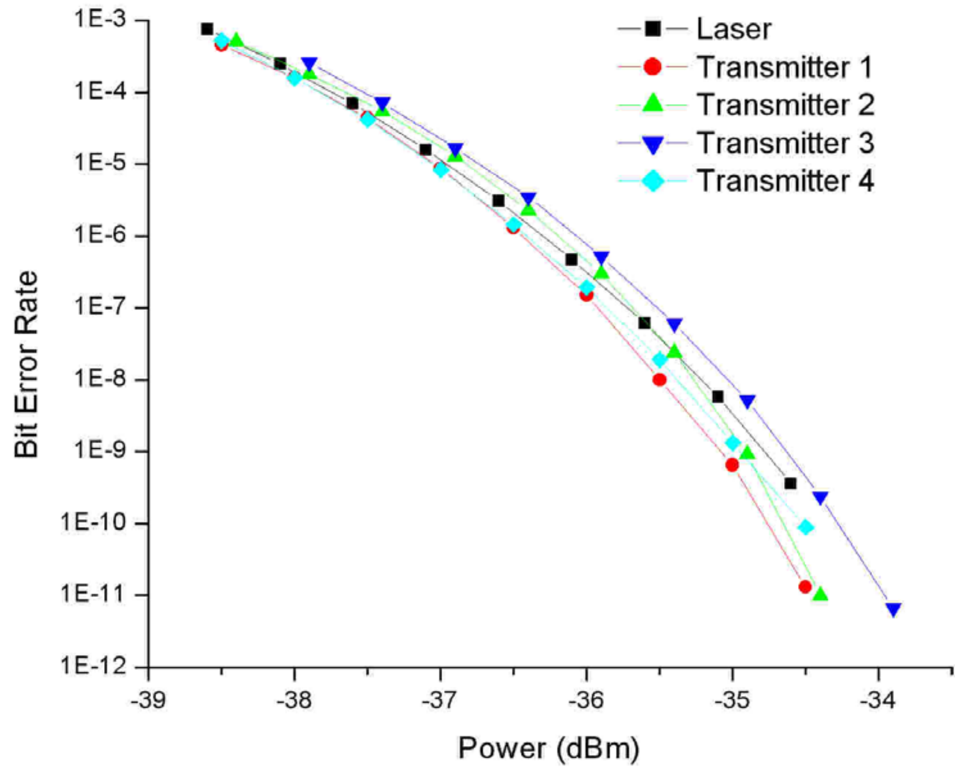


Transmitter 3



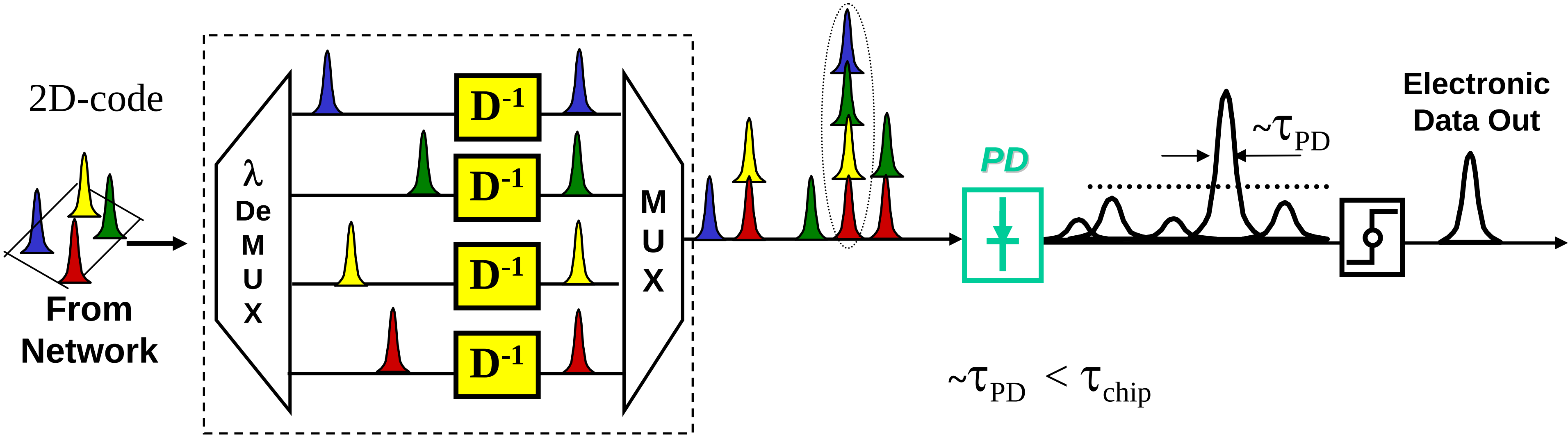
Transmitter 4

PD: *HP OC-48 Receiver*

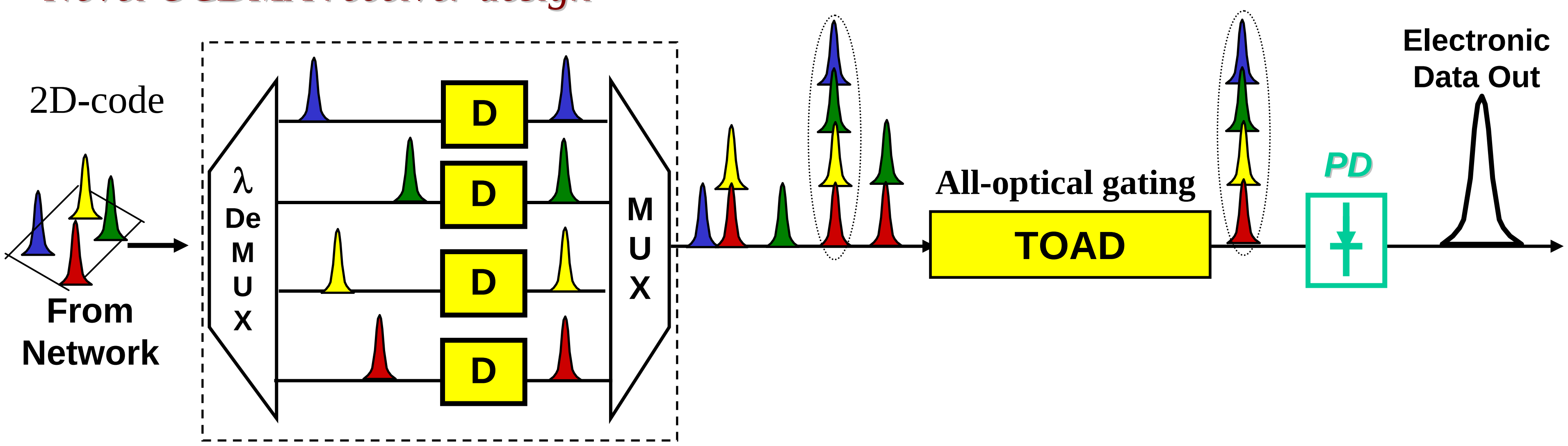


Eliminating MAI with 2ps time gating

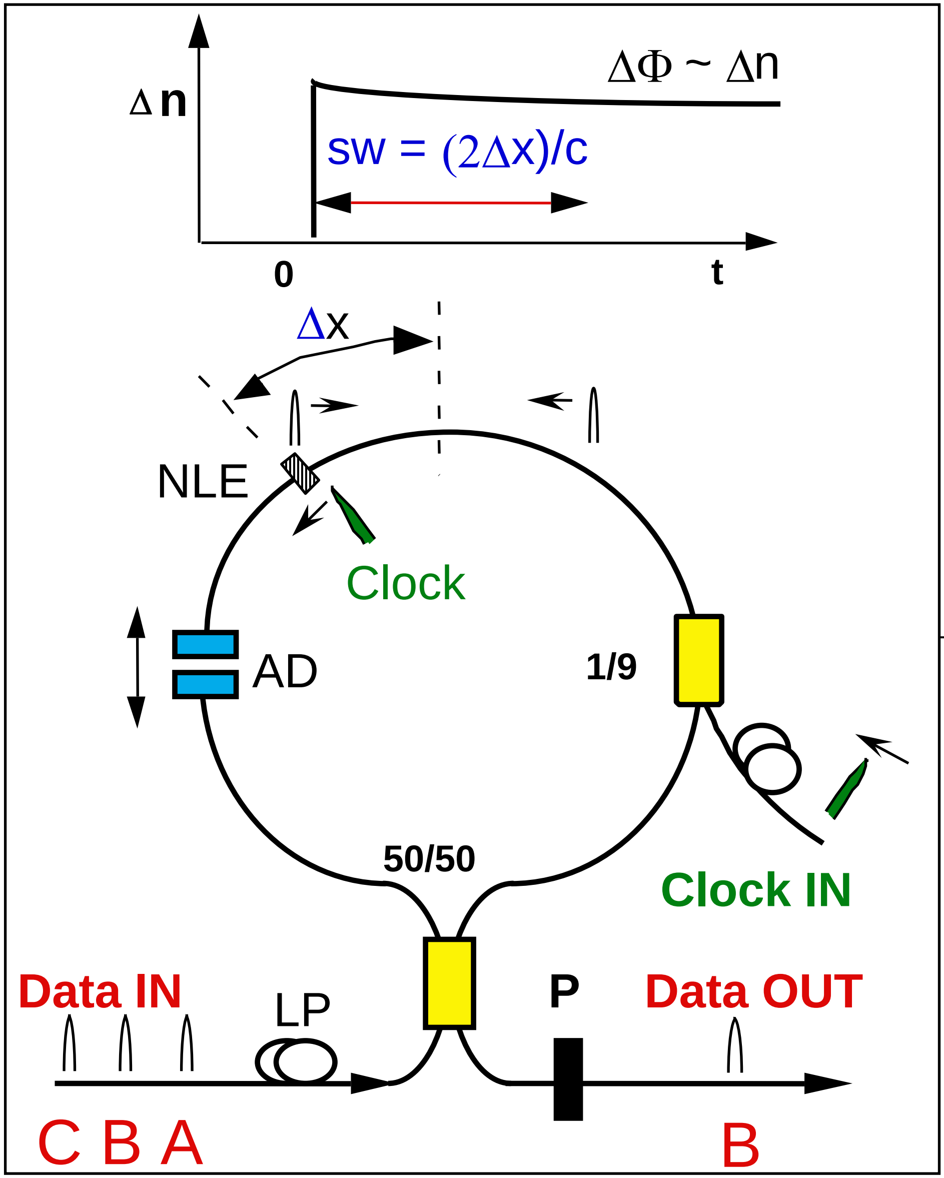
Conventional OCDMA receiver

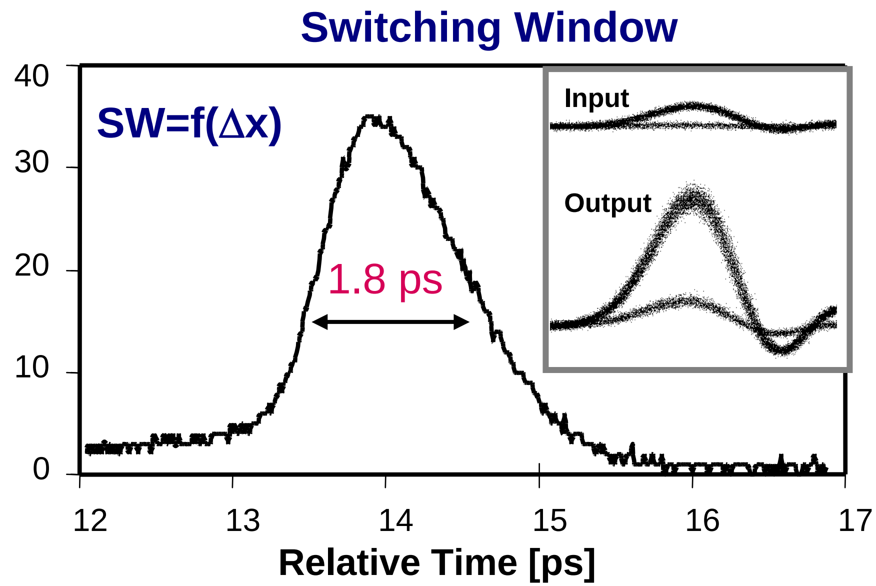


Novel OCDMA receiver design



TOAD -Terahertz Optical Asymmetric Demultiplexer





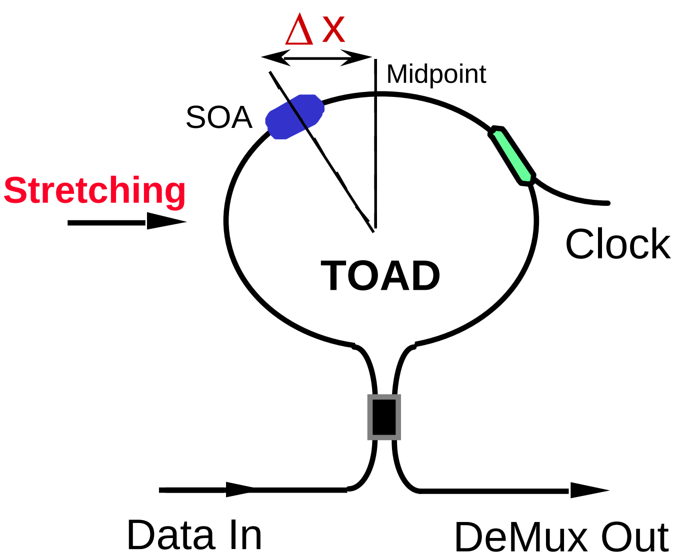
TOAD Properties

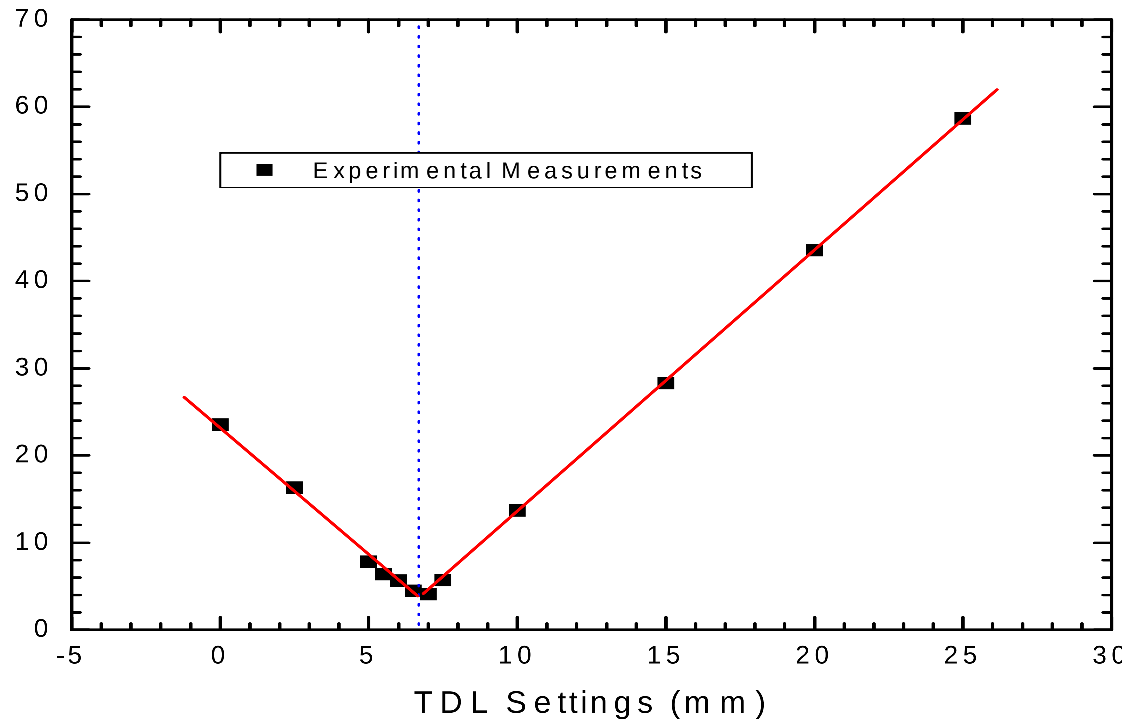
- Picosecond all-optical gating
- Low control pulse energy ~500fJ
- High SNR (BER < 10^{-9})
- Was integrated
- 6 dB gain

Glesk et. al., "Demonstration of All-Optical Demultiplexing of TDM Data at 250 Gb/s," Electronics Letters **30**, 339 (1994)

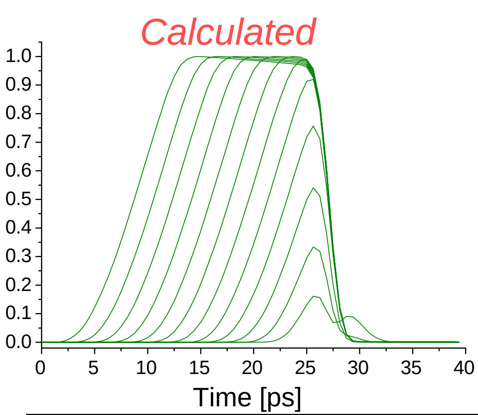
Switching Window is a Function of SOA Displacement

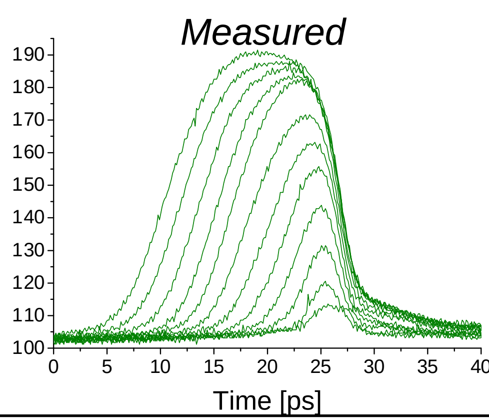
$$\frac{I_{Out}(t)}{I_{In}(t)} = SW(t) = \frac{1}{4}\left\{ G_1(t) + G_2(t) \pm 2\sqrt{G_1(t)\,G_2(t)}\cos(\phi_1(t) - \phi_2(t)) \right\}$$





TOAD Switching Windows (SW)

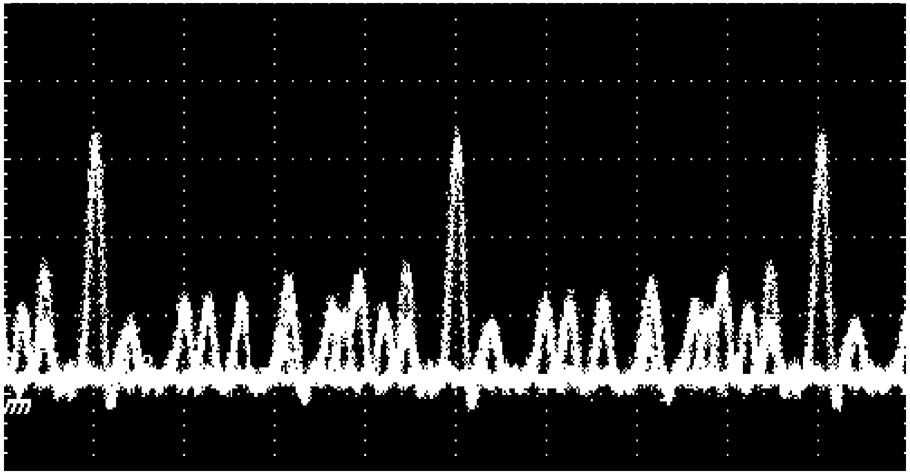




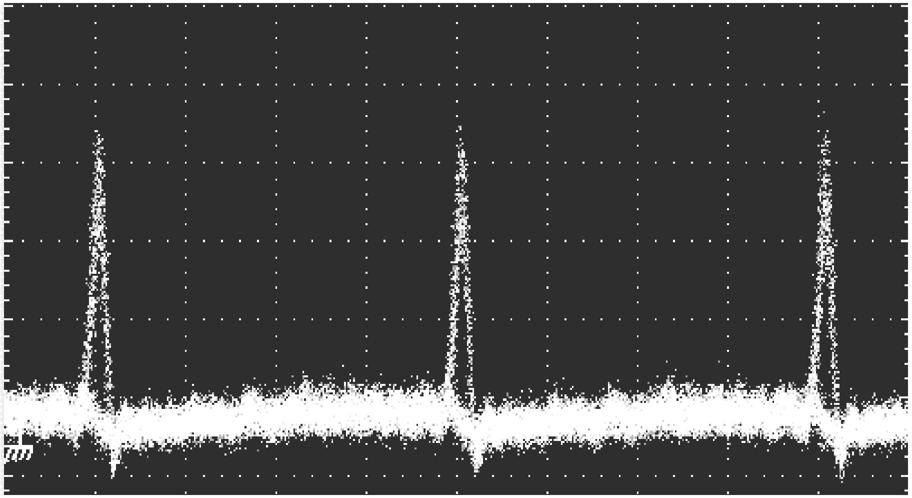
Glesk et. al., "Polarization Insensitive Terabit Optical Demultiplexers," *Proc. SPIE 2481*, p. 13 (1995). Invited paper

TOAD-based receiver demonstration

OCDMA Receiver – NO Time Gating

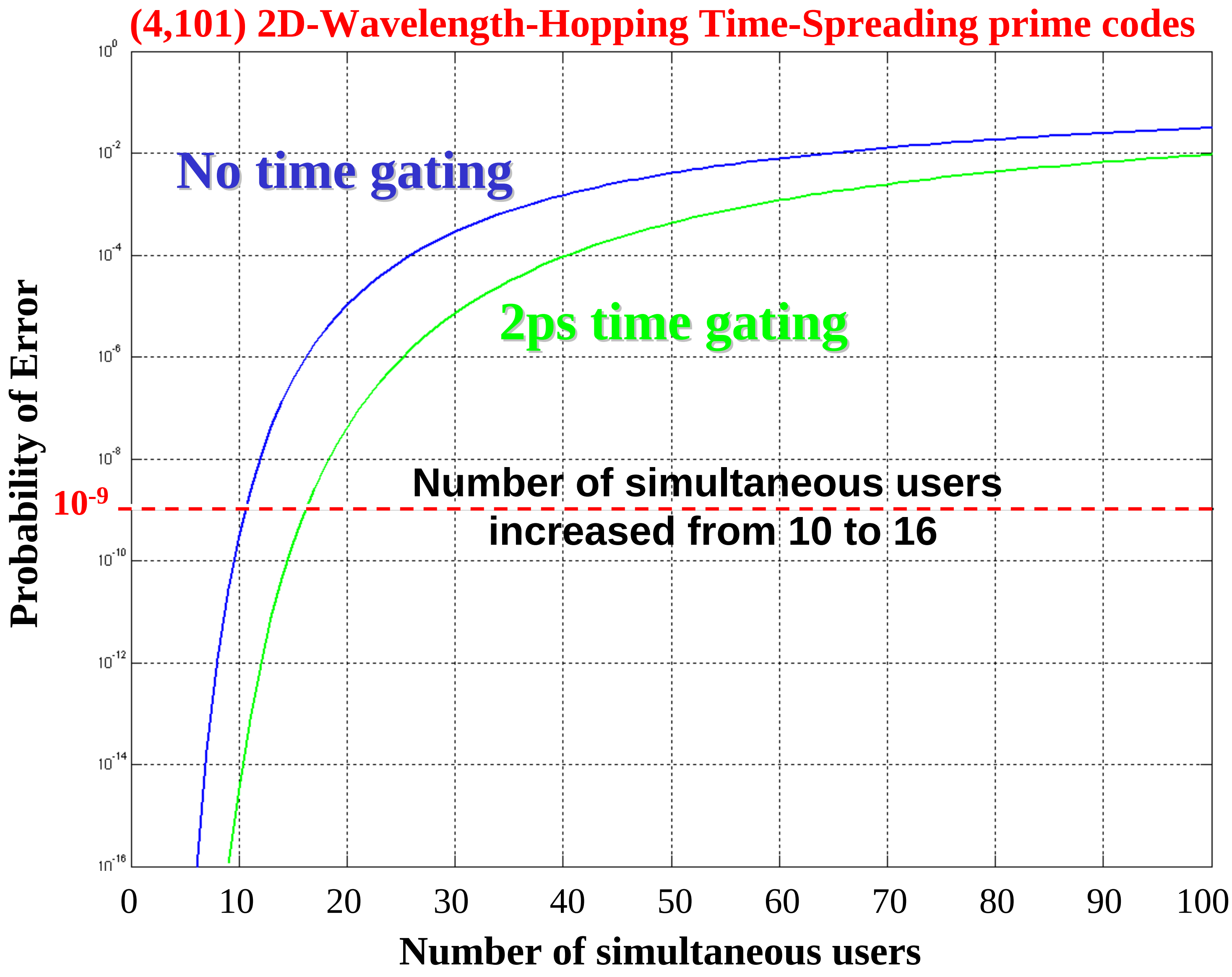


TOAD–based OCDMA Receiver



Achieved
BER < 10^{-9}

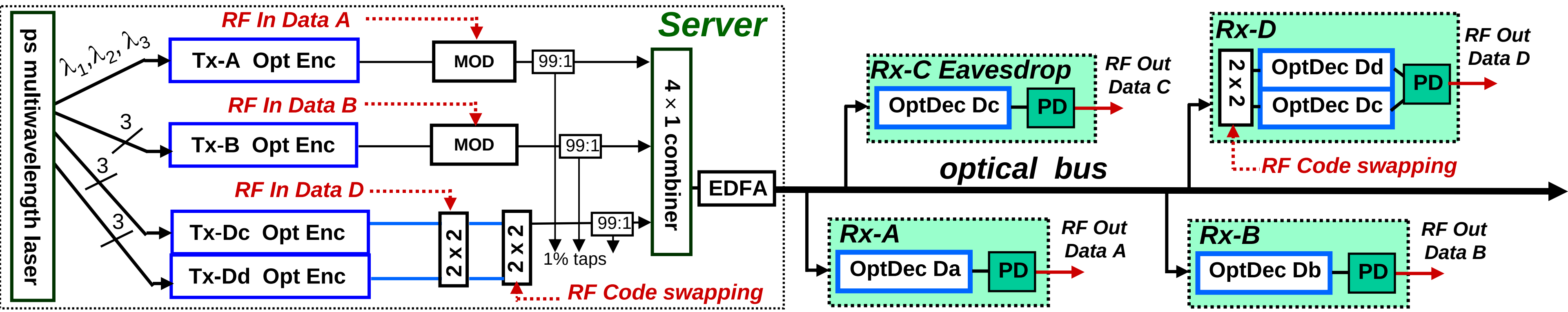
Performance improvement with all-optical time gating



Secure communication platform for avionics applications

In collaboration with Lockheed Martin

- OCDMA based
- bus network architecture



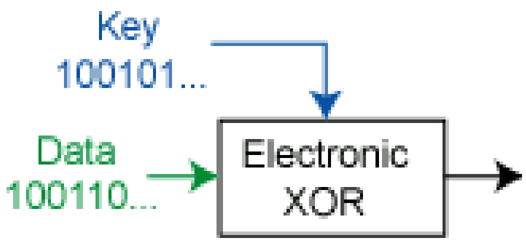
Special features:

- Multi-level Security for users
- Implemented *One-time Pad* in optical domain to secure data

I. Glesk, et al, "OCDMA platform for avionics applications," Electronics Letters 42 (19) 1115-1116 (2006)

Concept of One-time Pad

Traditional electronic XOR



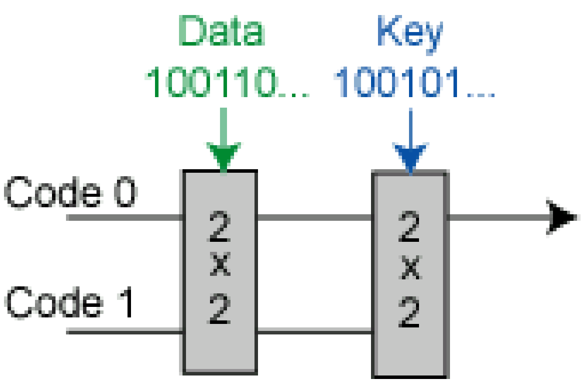
Electronic XOR

Problems:

– RF signature radiation which may be vulnerable to side channel attacks

– Electronic speed limited to a few GHz

Novel optical approach



Data	Key	XOR Out
0	0	0
0	1	1
1	0	1
1	1	0

Optical layer XOR

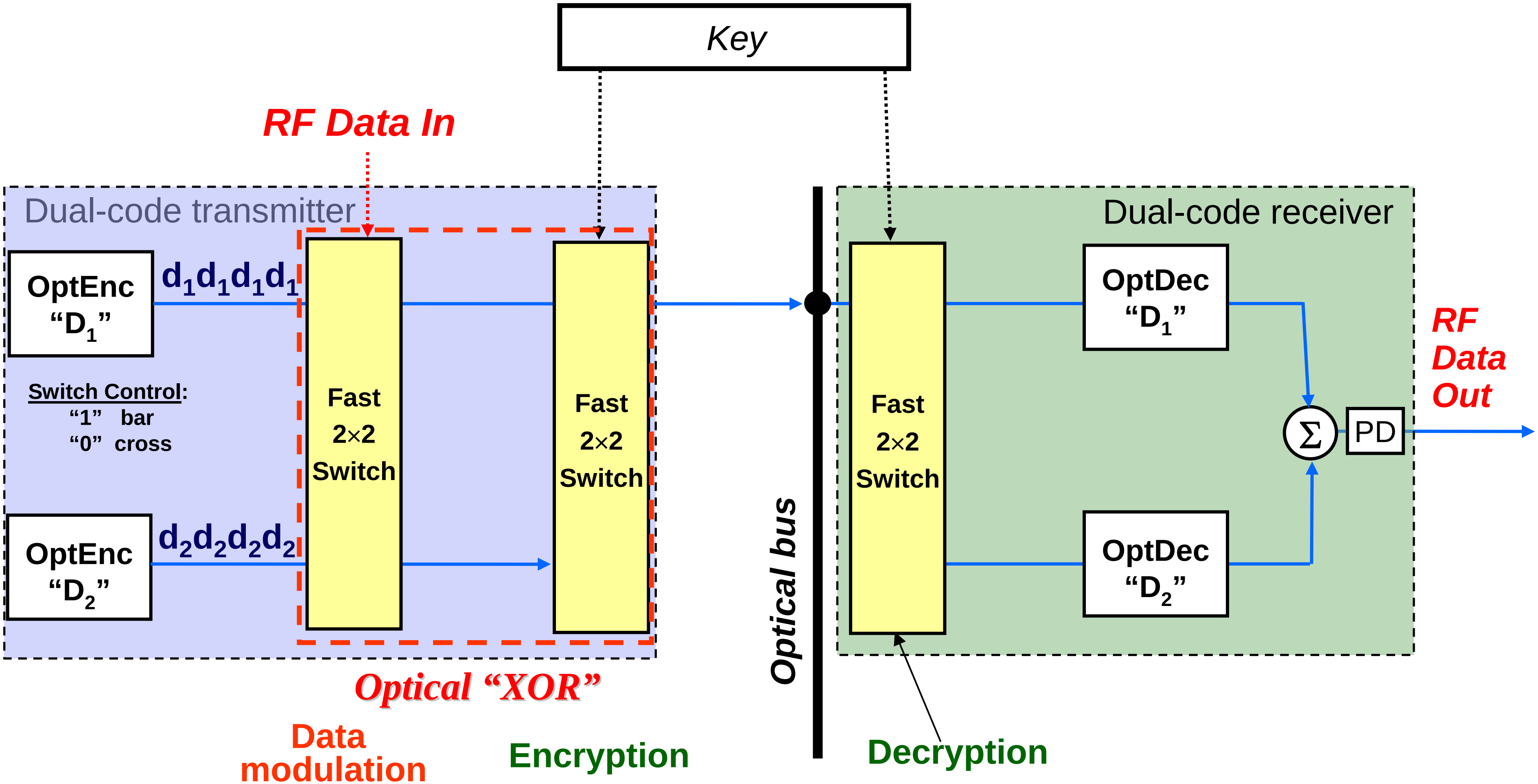
Advantages:

– Encoded data never exists in electronic form

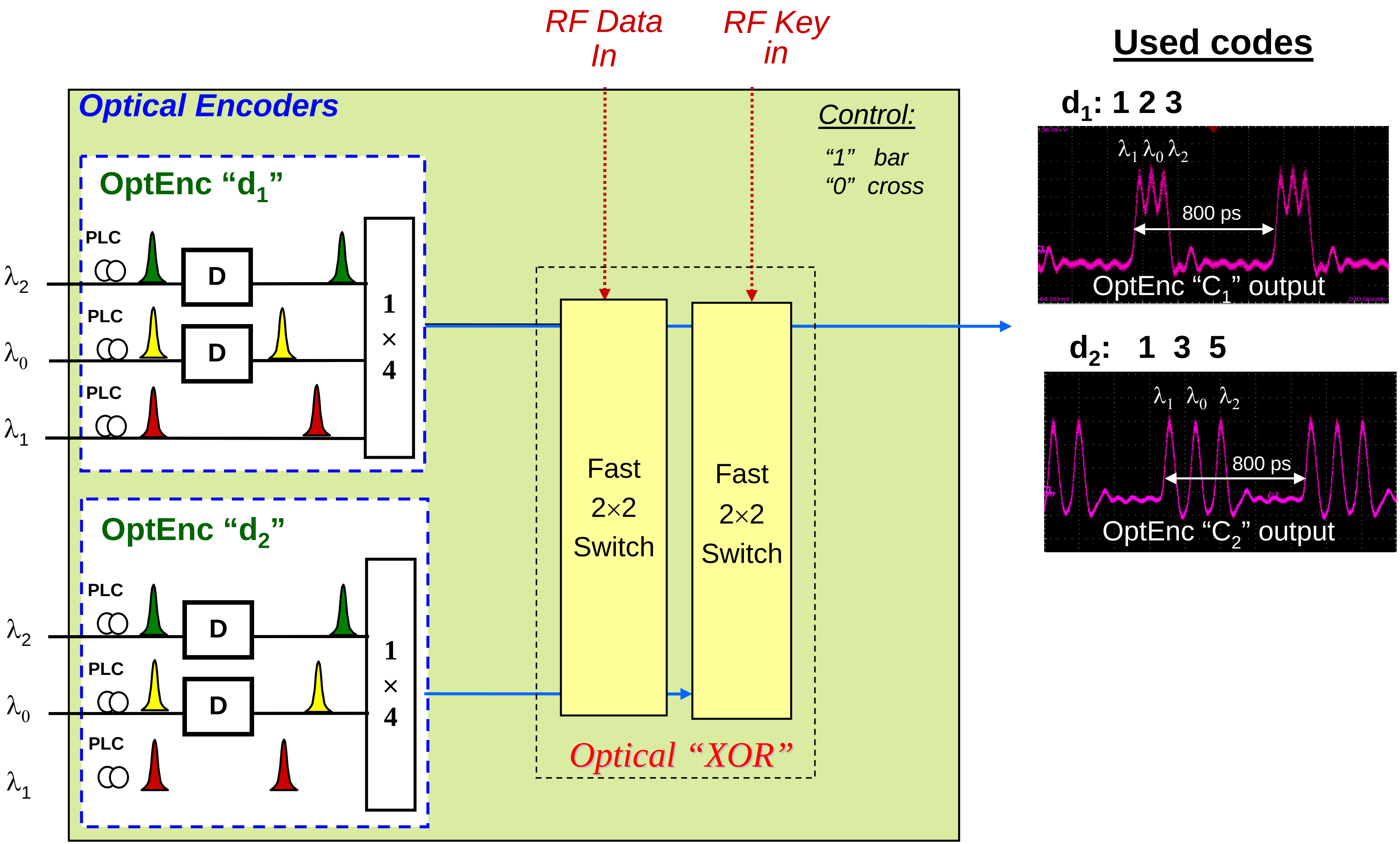
– No RF signature is generated

I. Glesk et. al, "Improving Transmission Privacy Using Optical Layer XOR," CLEO/IQEC, 2007, paper CThBB6.

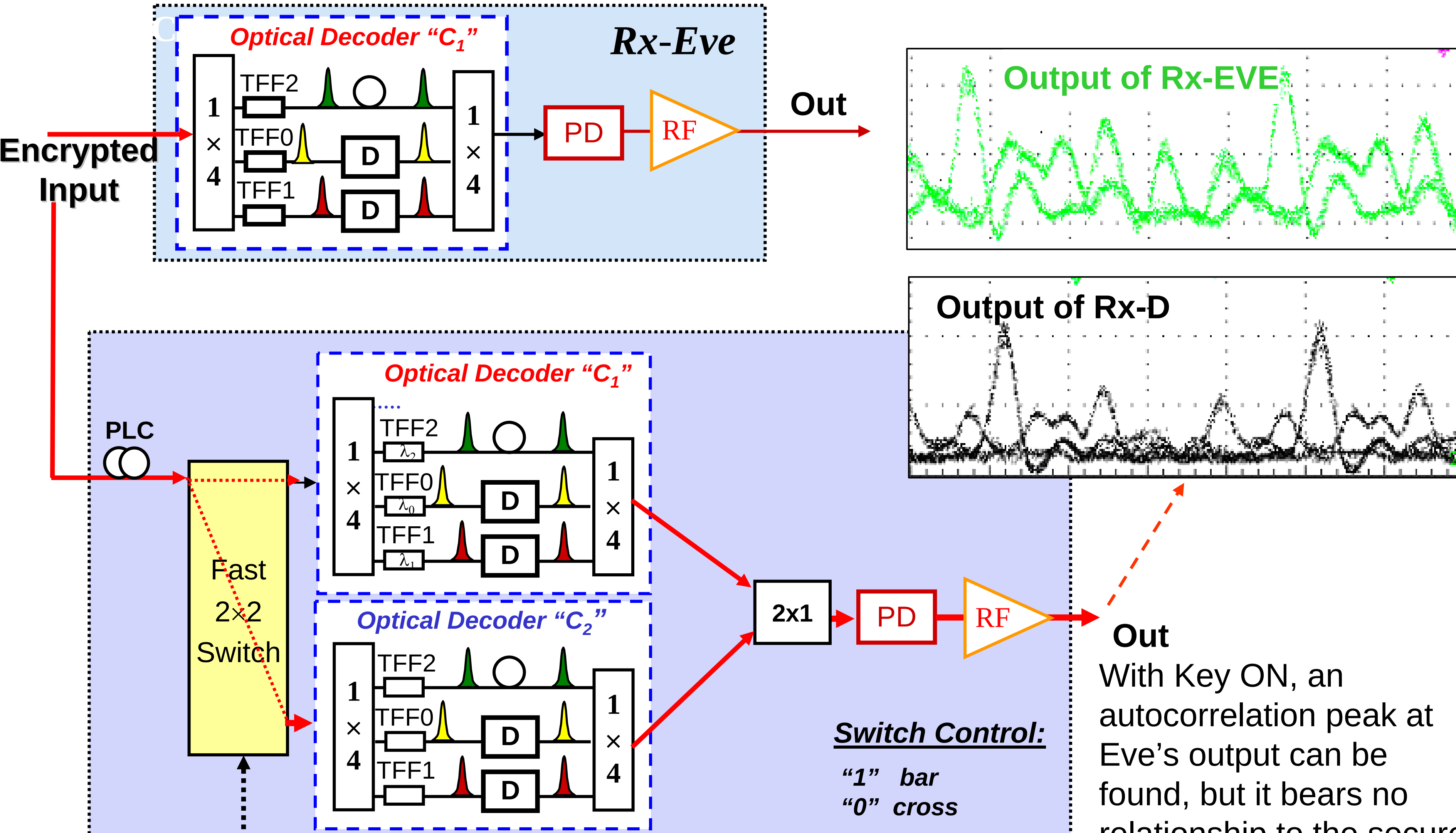
Optical implementation of One-time Pad



Experimental demonstration



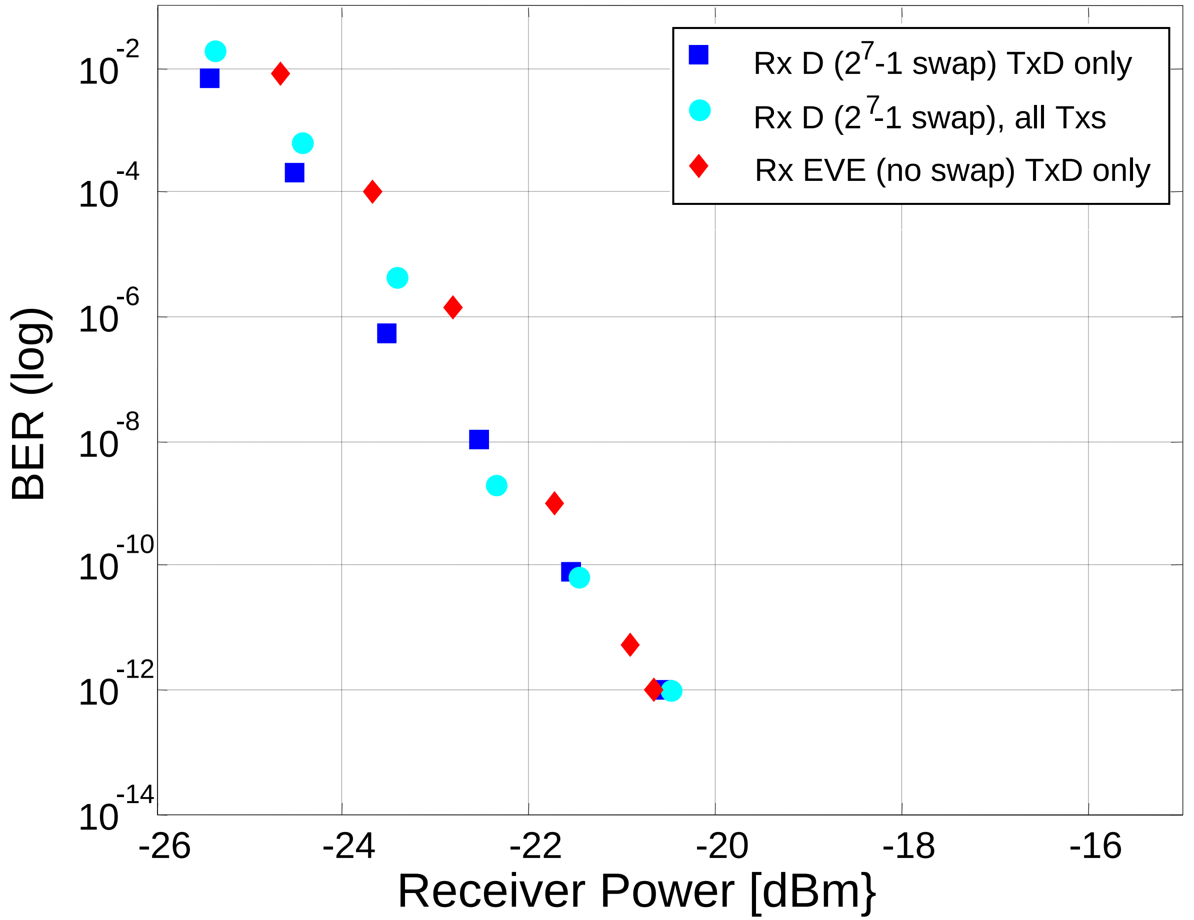
Operation of secure channel and eavesdropper



Out

With Key ON, an autocorrelation peak at Eve's output can be found, but it bears no relationship to the secure data itself.

key = 2^7 -1 PRBS sequence



When D does no code swap: One-time Pad OFF

– EVE can eavesdrop with good performance (red diamonds)

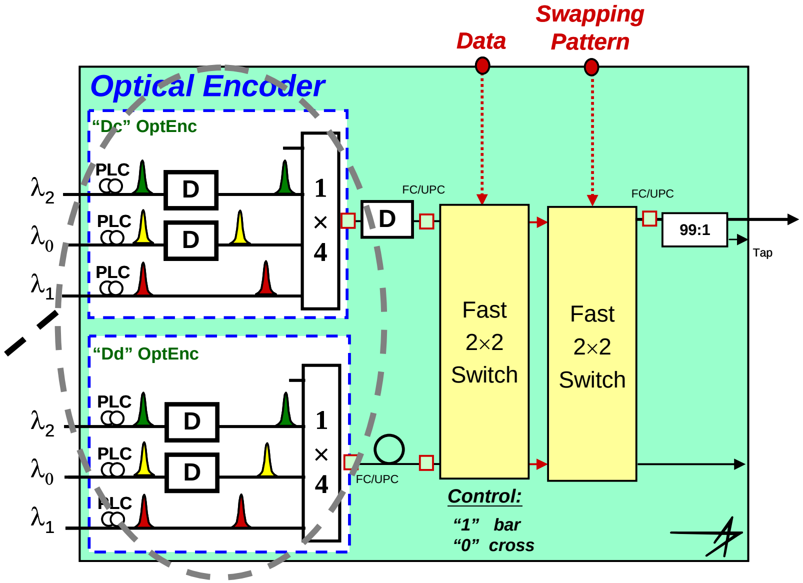
When D does code swap: One-time Pad ON

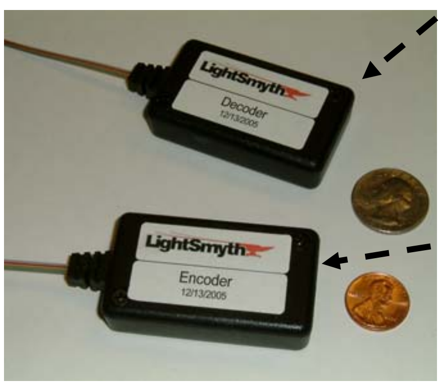
– EVE cannot eavesdrop, data cannot be received, no BER can be obtained

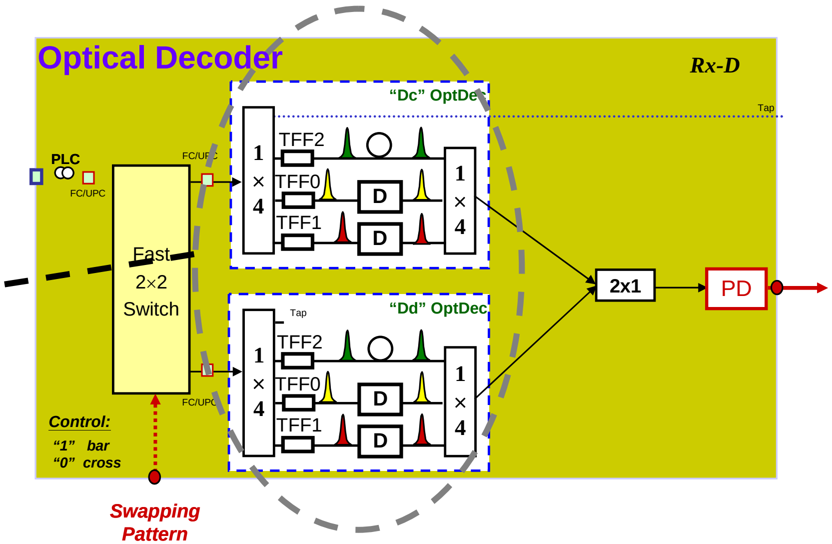
Path to miniaturization

Path to miniaturization through integration

Thin film filters* (TFFs)** in combination with ***fiber delay lines



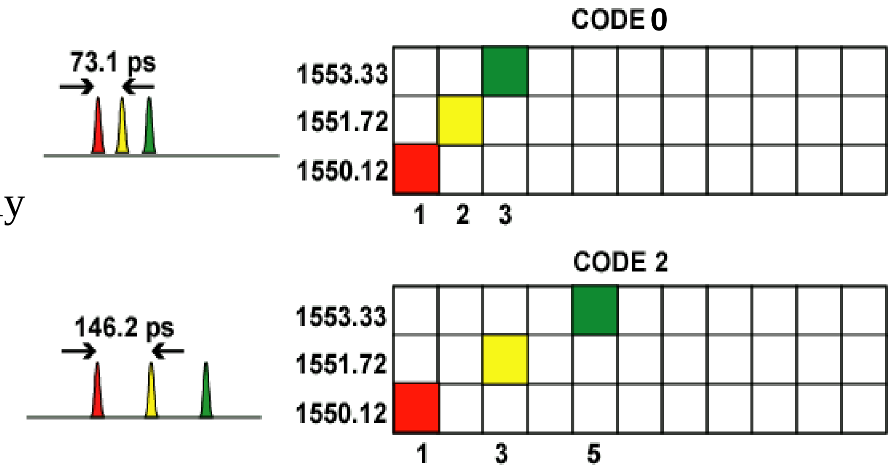


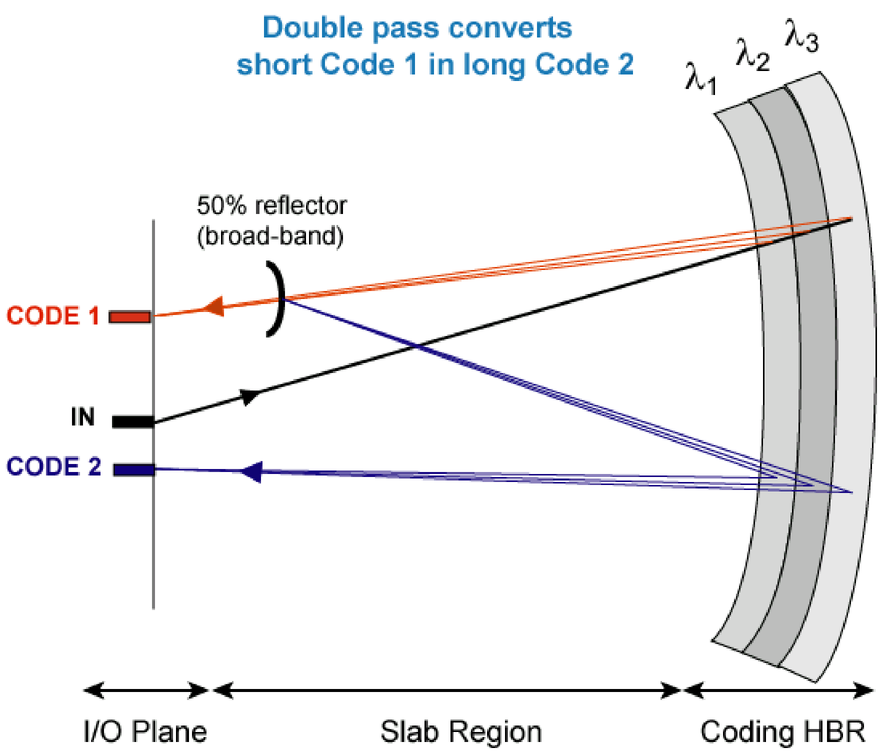


Holographic Bragg Reflectors
(HBRs)

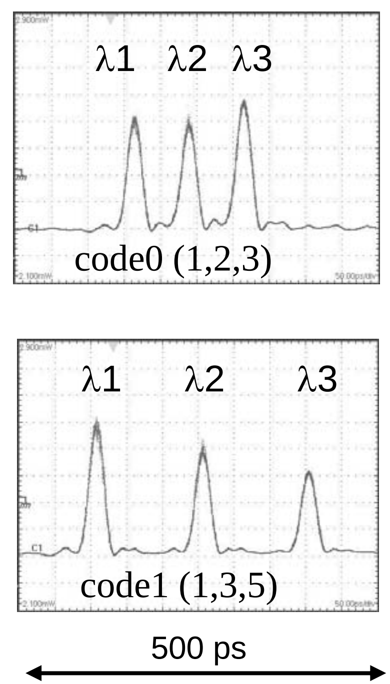
HBR-based Dual code Encoder/Decoder

Single device can process two 2D codes simultaneously including wavelength selection

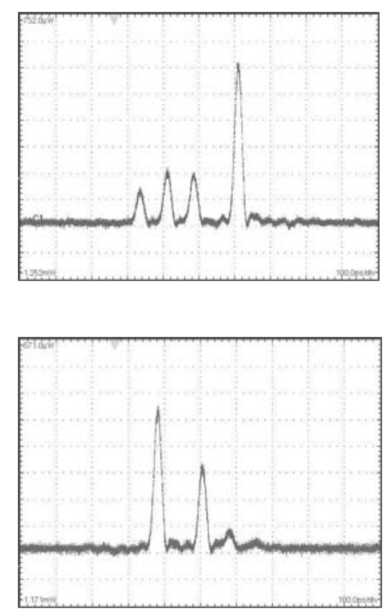




HBR Dual Encoder

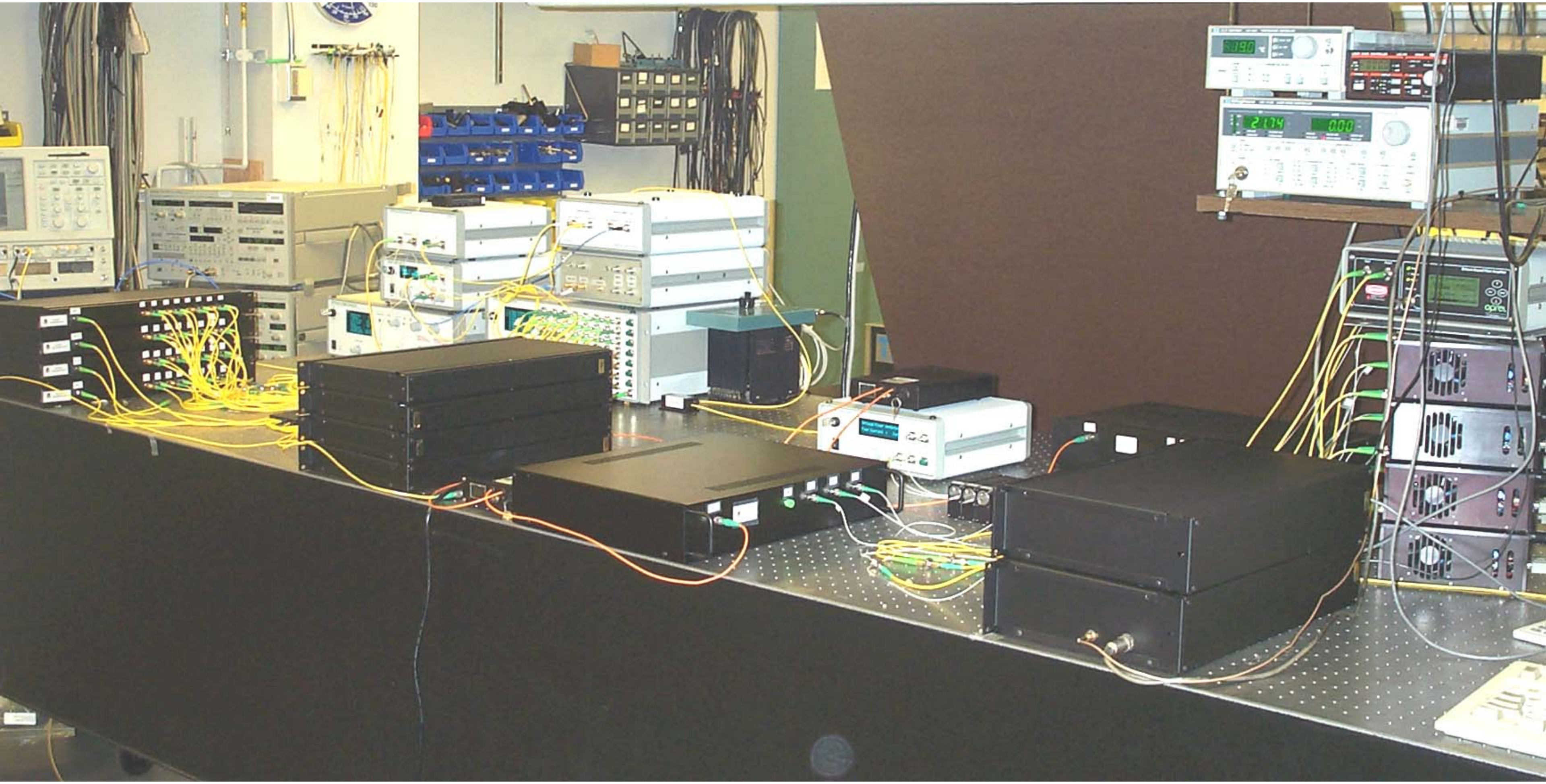


HBR Dual Decoder



Scaling OCDMA systems with multilevel encoding

Princeton's OCDMA testbed to demonstration M-ary encoding

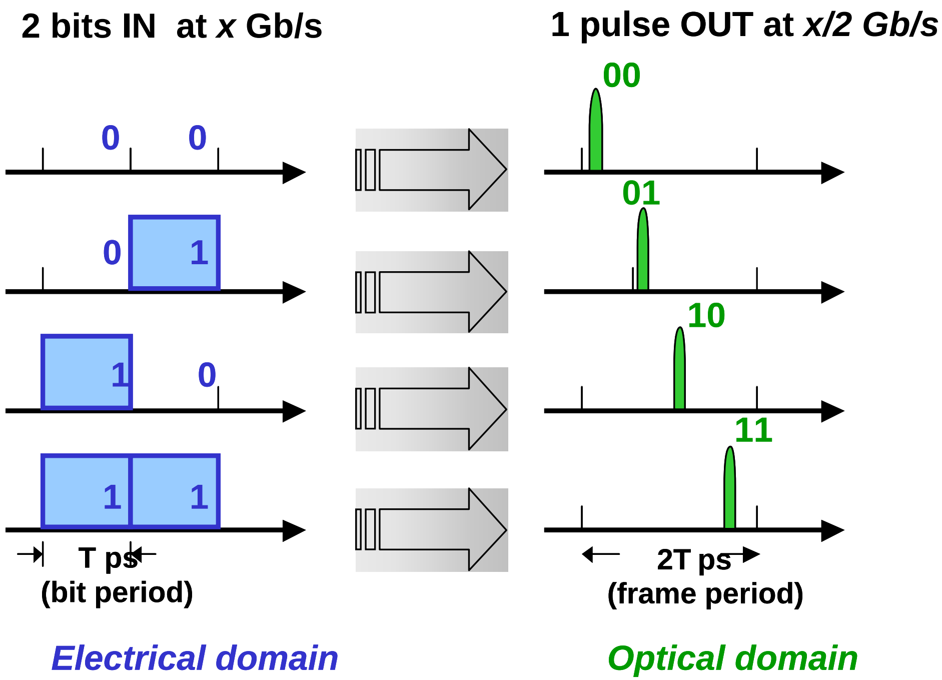


M-ary concept

- Motivation:
  - Higher spectral efficiency

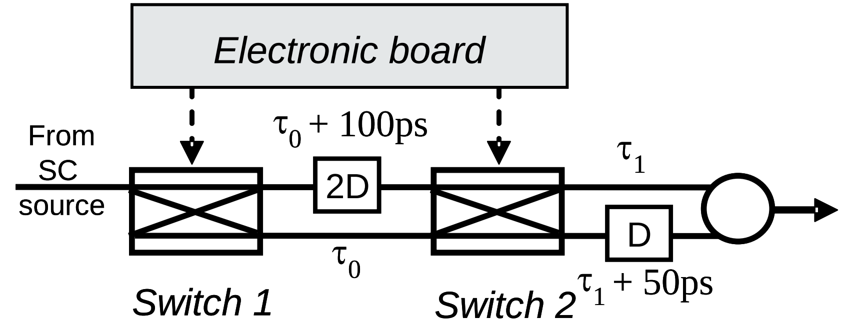
    M-ary sends multiple bits of information per one symbol transmitted
- How?
  - Uses pulse positioning (PPM)
  - Needs all-optical method for symbols decoding at high data rates
- We implemented M-ary with 4 levels
  - Hardware can operate at a lower rate
  - Converts 10Gb/s rf data to 5Gsymbol/s M-ary

Concept of M-ary Encoder



PPM M-ary encoding architecture and symbol correspondence

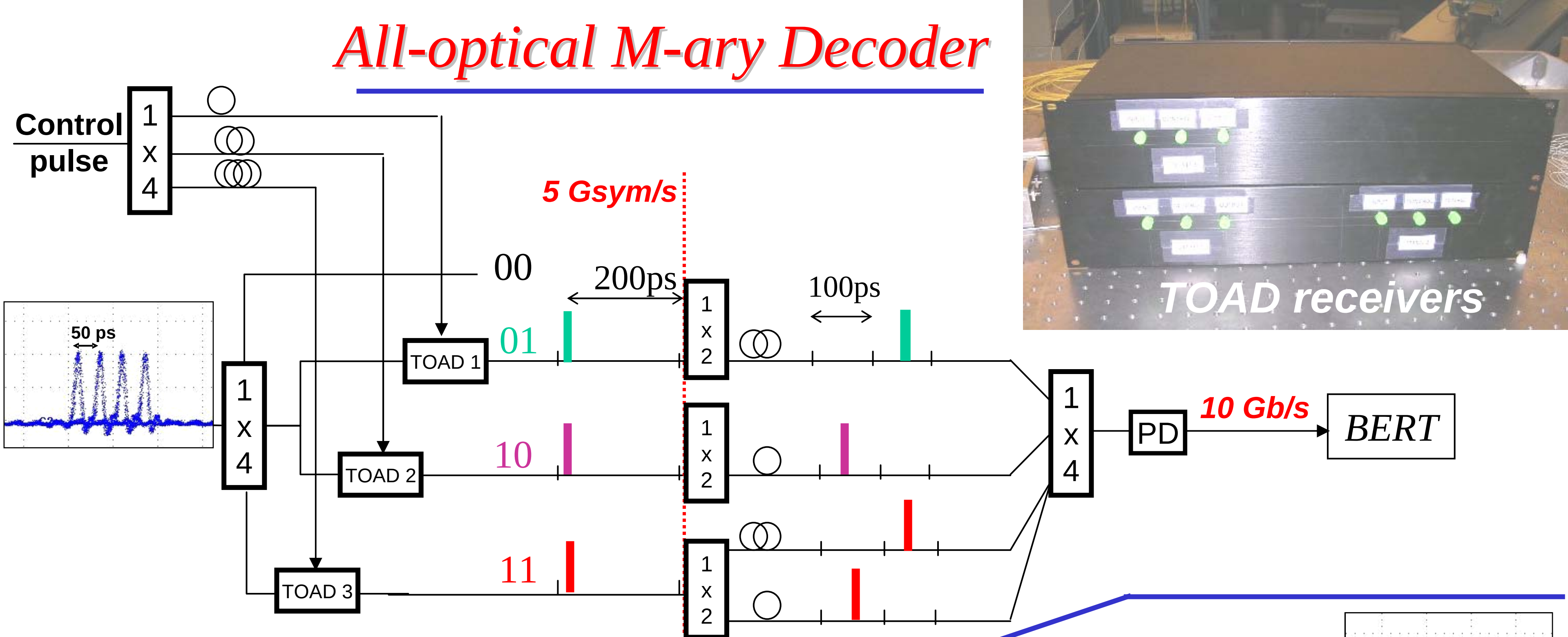
Data	00	01	10	11
(C_1 C_2)	(0 0)	(0 1)	(1 0)	(1 1)
delay	0ps	50ps	150ps	100ps
symbol	S0	S1	S2	S3



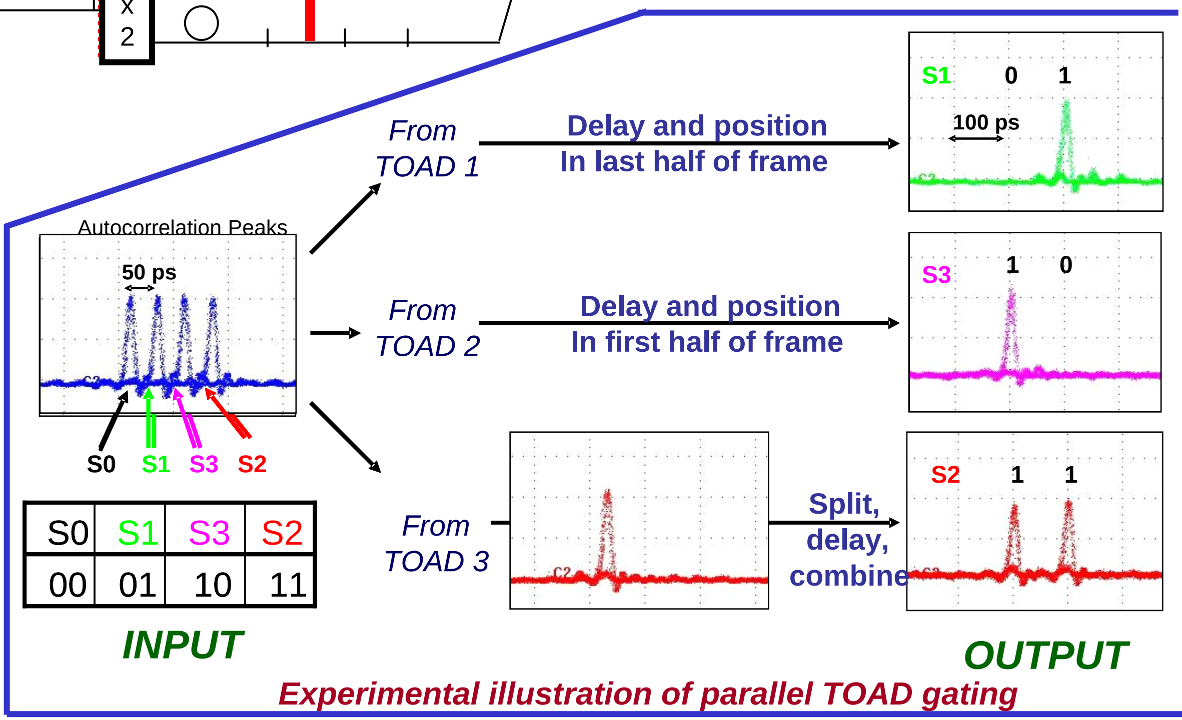
- We implemented M-ary modulation with 4 levels
  - Increases number chips in code sequence by converting 10Gbps data to M-ary at 5G (each M-ary symbol contains 2 bits of information)

C-S. Brès et al, “Novel M-ary Architecture for Optical CDMA using Pulse Position Modulation,” IEEE LEOS Sydney, Australia, 2005, paper ThBB1

All-optical M-ary Decoder

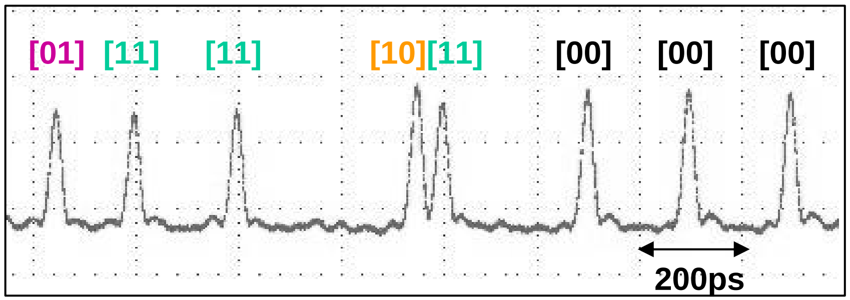


- Pulse is present in one and only one PPM slot:
  - Position pulse back within the 100ps bit according to the M-ary code received
  - "00" symbol can be used for clock recovery

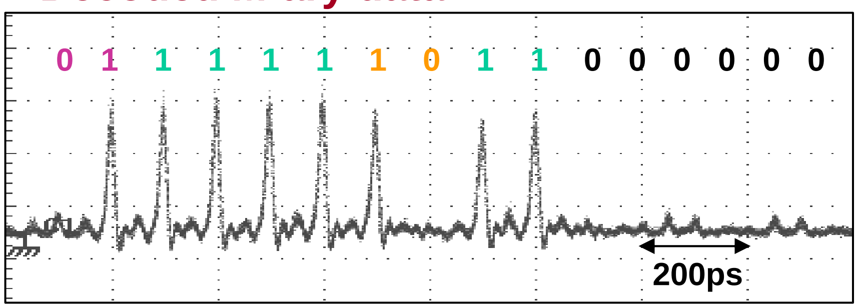


Experimental Results

Encoded M-ary data



Decoded M-ary data

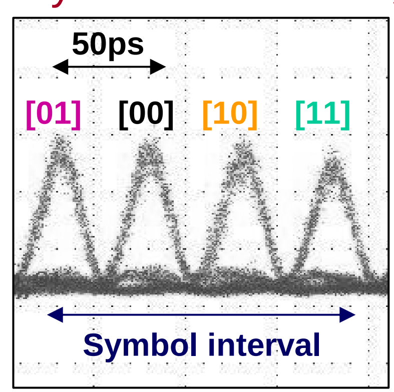


- Encoded M-ary data:
  - 1 pulse per symbol (00, 01, 10 or 11) within 200ps
- Decoded M-ary data:
  - Original 10Gb/s data recovered
  - Pulses equally spaced every 100ps

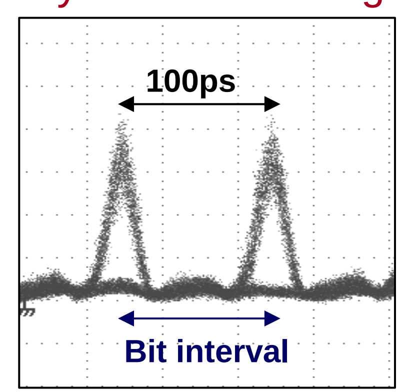
- Eye patterns:
  - Random superposition of the 4 PPM slots: 4 eyes within 200ps, 50ps apart
  - Recovered pattern: 10Gb/s eye

M-ary decoding

Eye before decoding

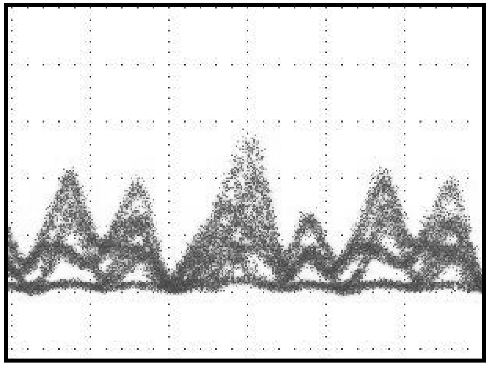


Eye after decoding

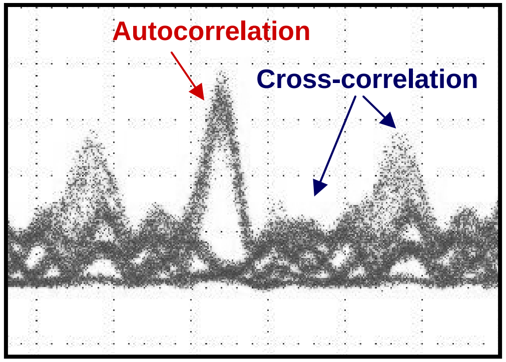


Additional All-optical signal processing is added

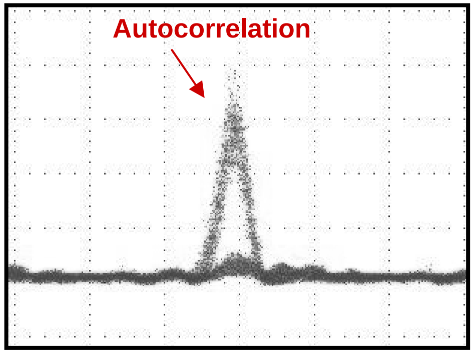
Before OCDMA decoder



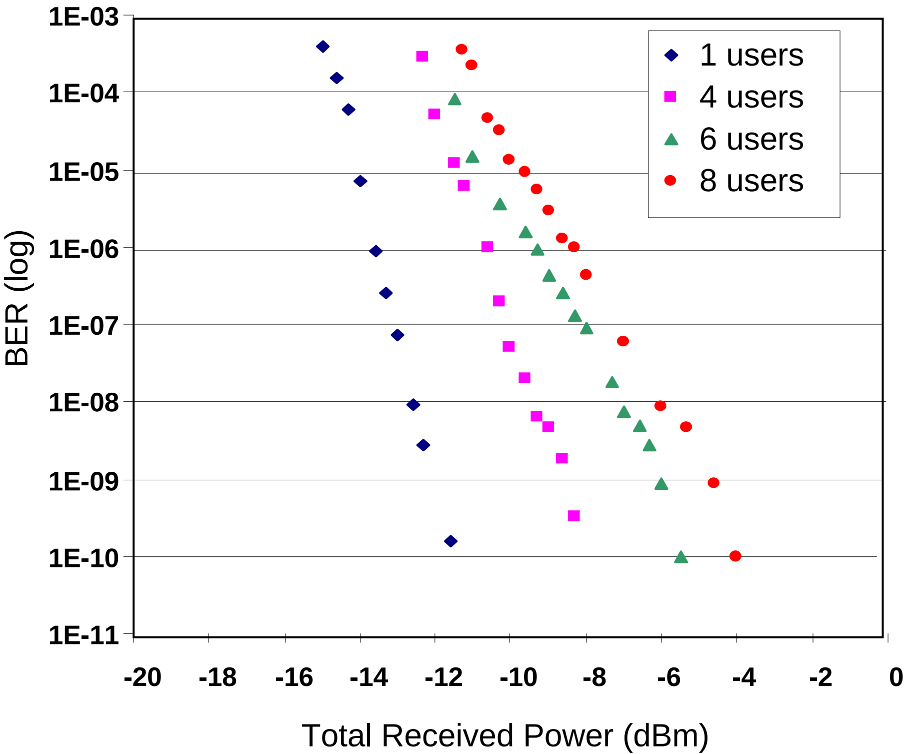
After OCDMA decoder



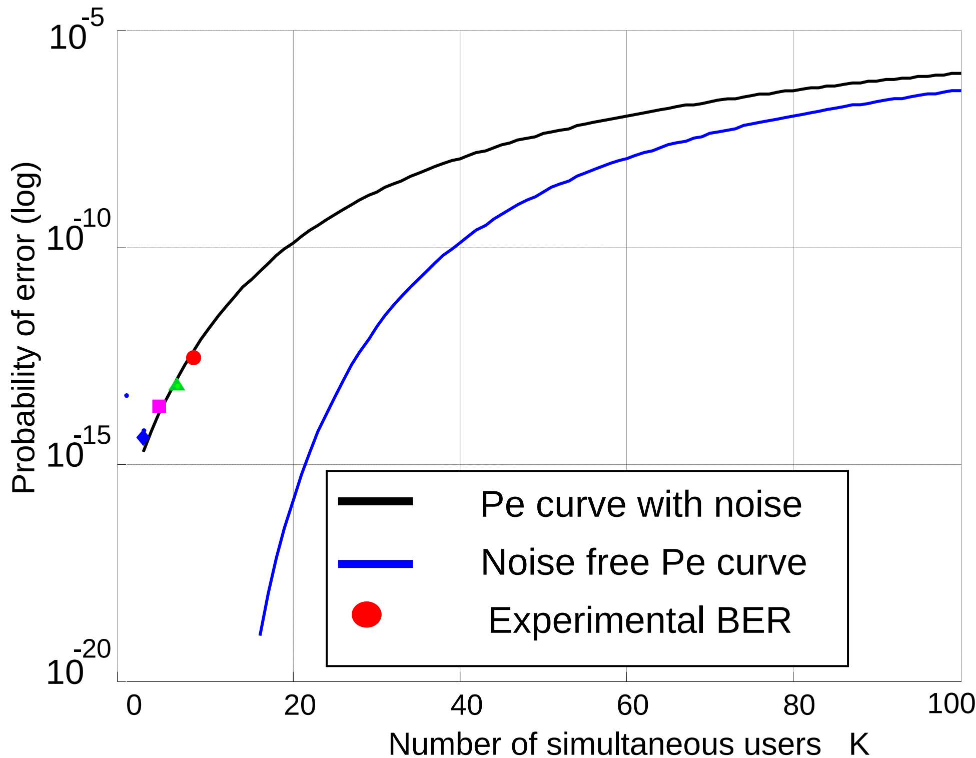
After TOAD time gating



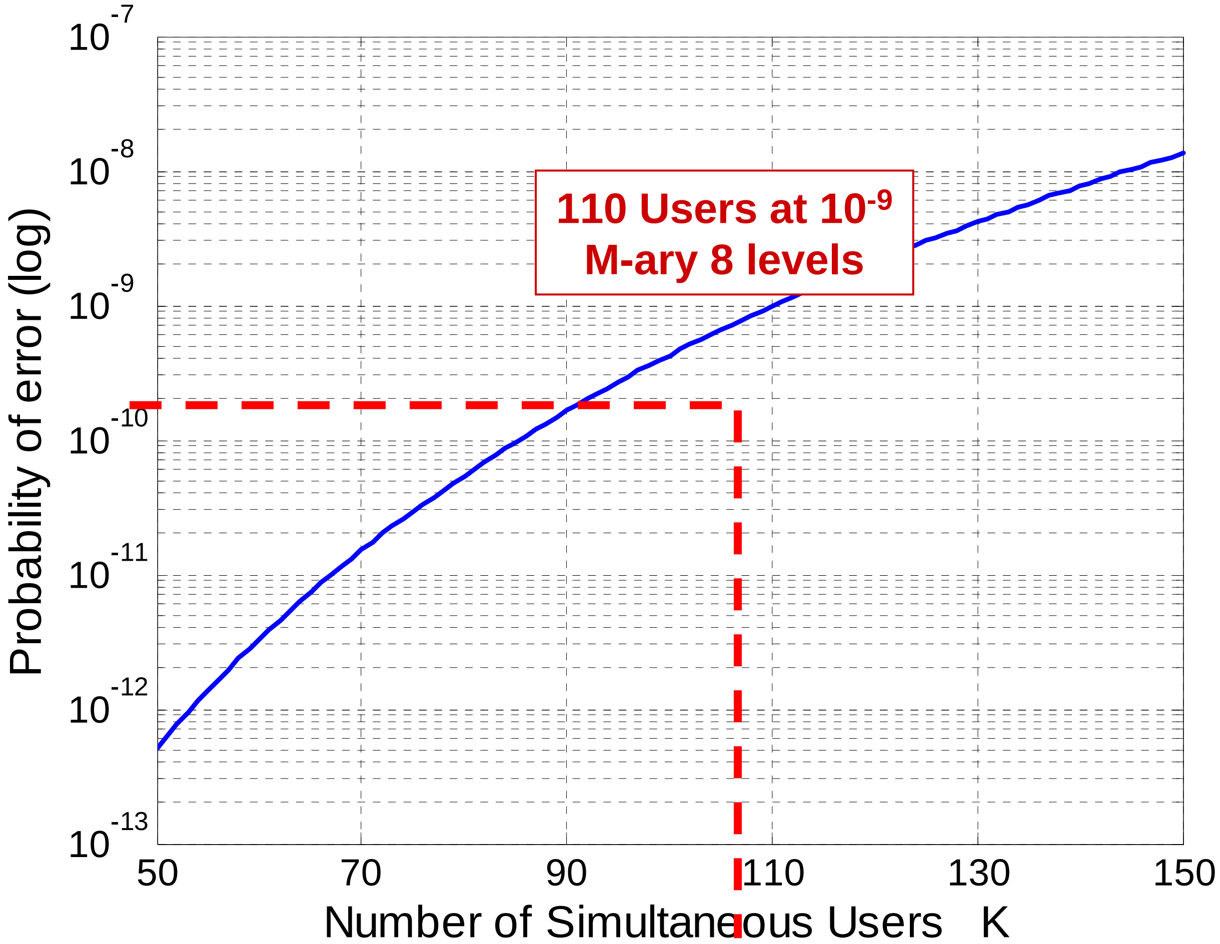
Experimental BER for Tx3 for 1 to 8 user case



Comparison of theory and experiment



Scaling using M-ary 8 levels



code weight = 8

Number of simultaneous users @ 10^{-9} BER = 110

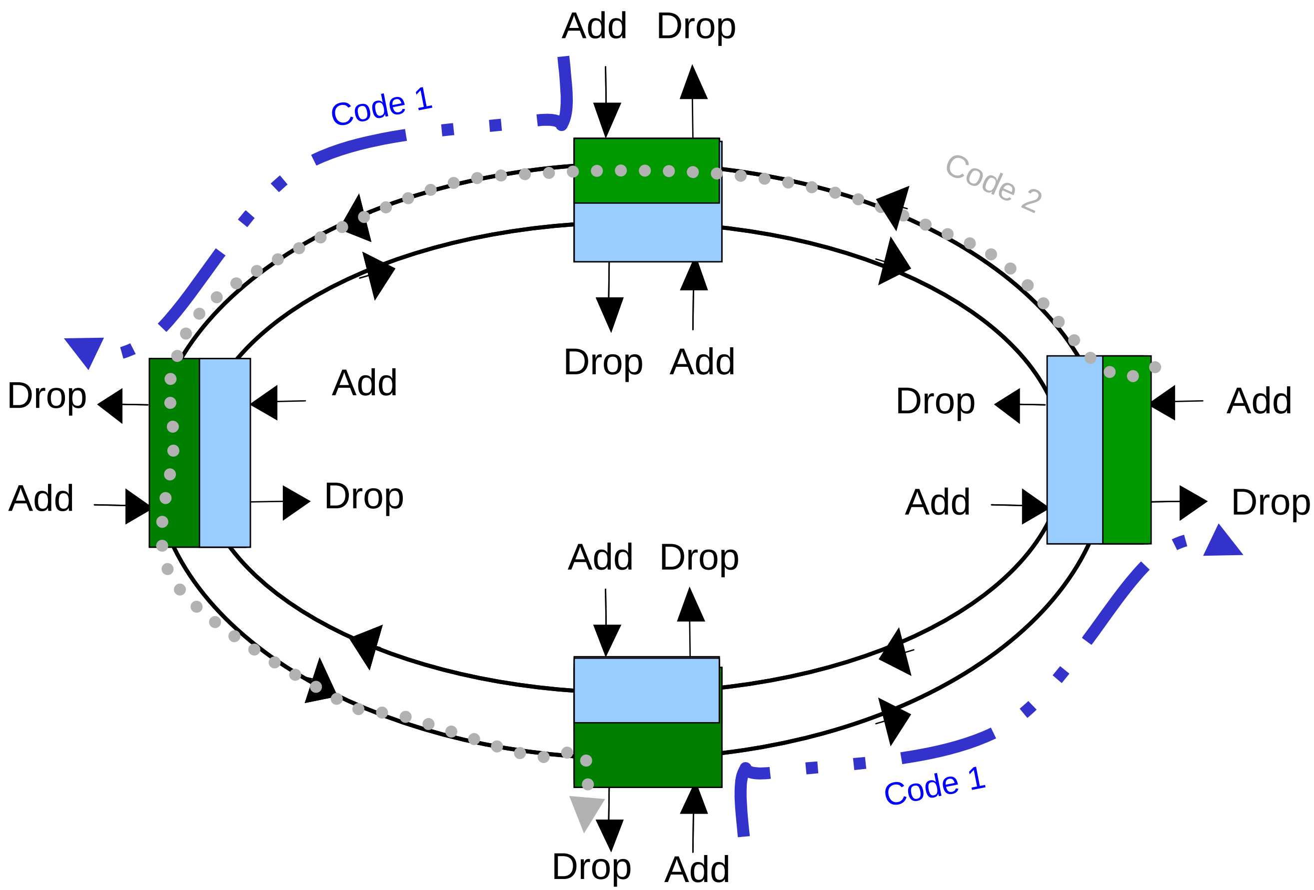
$$SE = \frac{110\ users \times 10\ GHz}{13 \times 75\ GHz}$$

$$SE = 112.8\ \%$$

$$cardinality\ \ \phi = 1369$$

Management of Optical CDMA Ring

Add/Drop Code Multiplexers for OCDMA Ring Network



1. Ring with code add/drop, code lives only between add / drop points

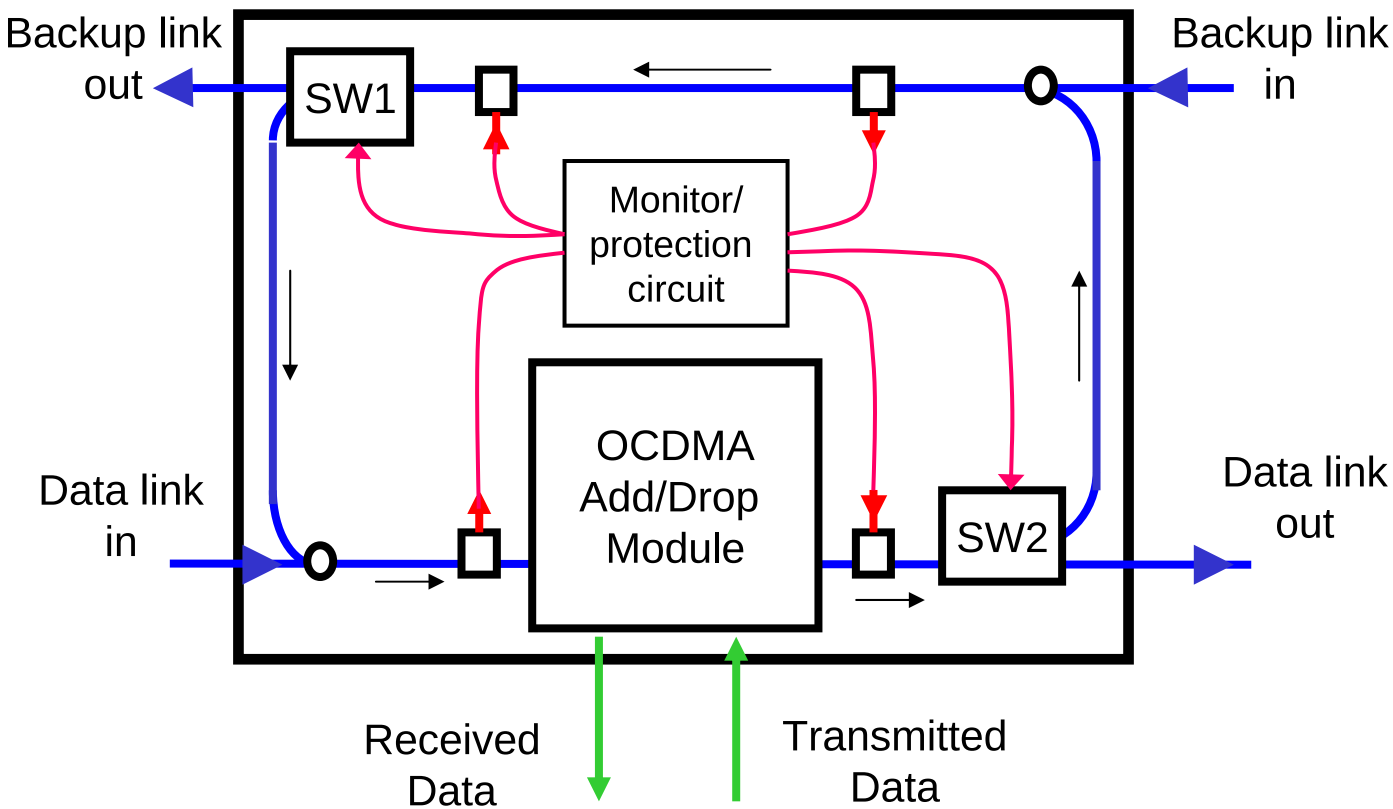
- Avoids interception of data by downstream nodes
- Code can be reused in separate parts of ring
- Enables scaling size of ring by code re-use

2. **Full interconnection possible without switching**

Add/Drop Code in OCDMA Ring Network

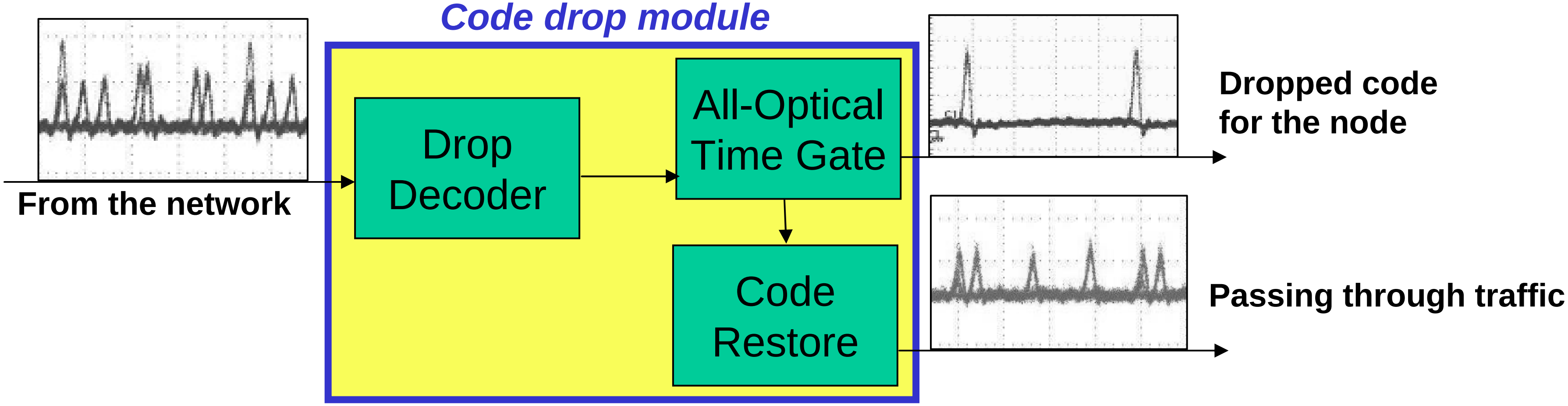
Topology of Self-Healing OCDMA Node with Distributed Processing

Each node monitors the integrity of fiber optic link in both directions.
Protection switches SW1 & SW2 reroute the data if a node/link failure is detected.

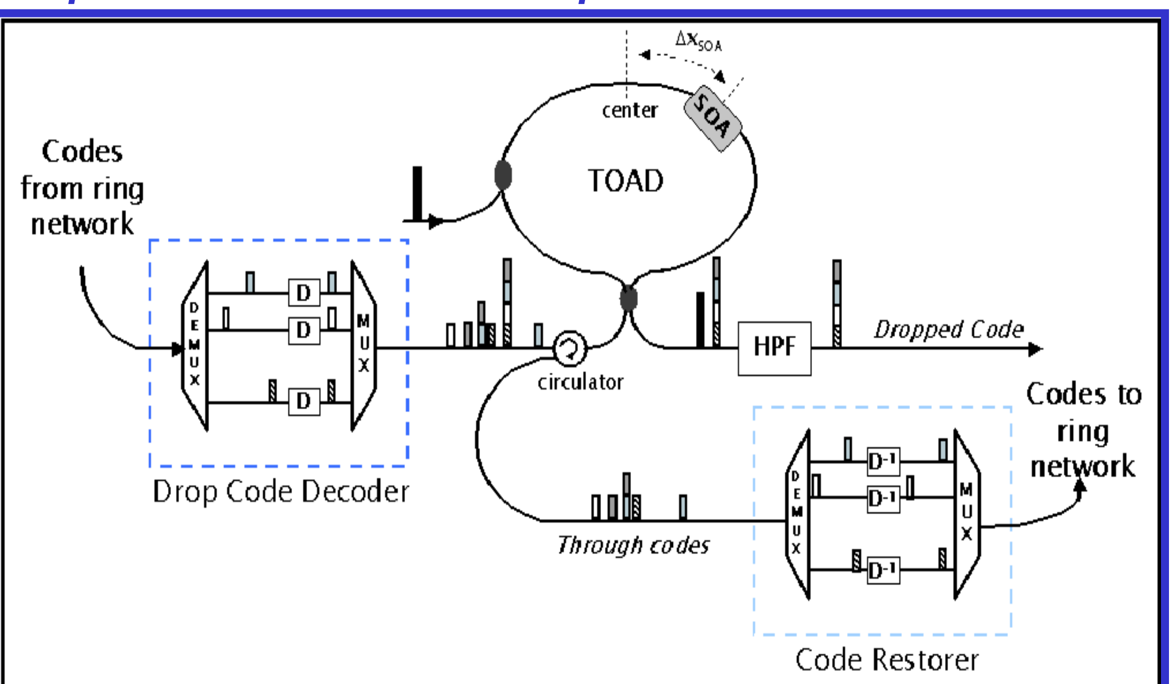


Demonstration of code removal from OCDMA ring

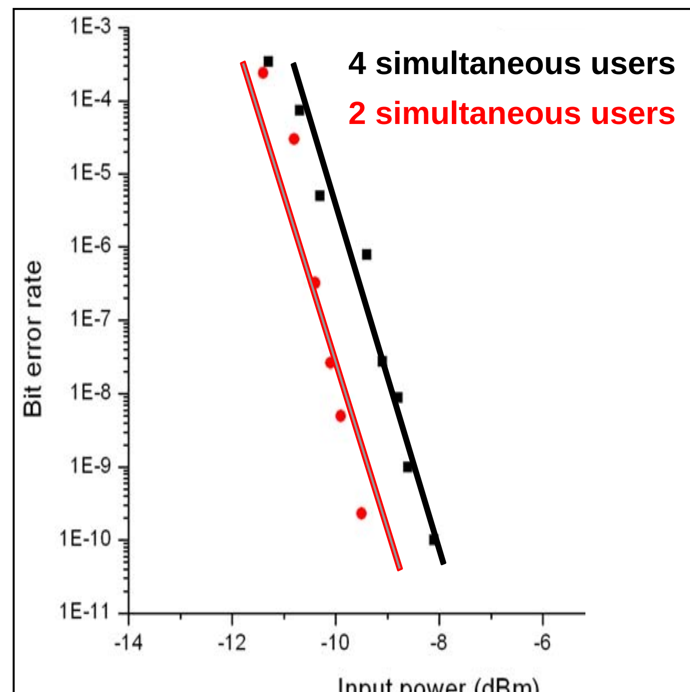
Code drop module



Implementation of code drop module



Performance - 2 & 4 users



Brès et al., IEEE Photon Tech Lett VOL. 17, No. 5, MAY 2005

Conclusion

- **OCDMA system improvements through all-optical signal processing**
  - 2ps time gating was used
    - it significantly increased number of simultaneous users
    - improved system's power budget
  - Implementation of One-time Pad in optical transport layer was developed and demonstrated
  - multilevel data security achieved in the system

- **Developed and demonstrated M-ary coding scheme to increase scalability and spectral efficiency**
  - PPM M-ary approach was developed for use with OCDMA transmitters and receivers using 2D-WHTS codes
  - The approach relaxes hardware and coding constraints

- **OCDMA ring network architecture was investigated**
  - All-optical signal processing was implemented to manage codes
    - A novel OCDMA "code drop" filter was developed and demonstrated