Lightpath Tracing in Photonic Networks

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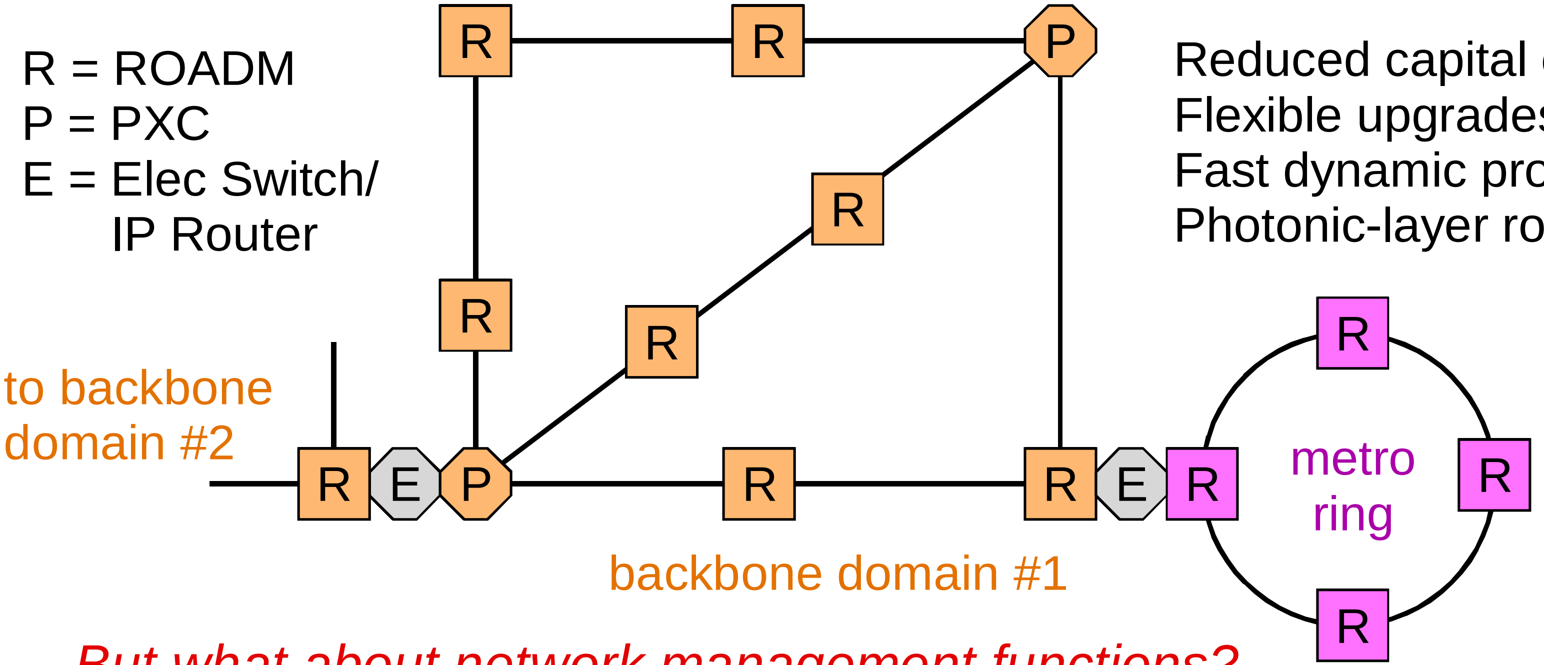
I. Photonic networks & lightpath tracing
II. LightLabel encoding and performance
III. LightLabel experiments - single user
IV. LightLabel experiments - multi-user

Photonic Networks

Photonic networking: Flexible routing of wavelengths w/o OEO conversions.

Cut cost by eliminating transponders and downsizing switches/IP routers.

Reconfigurable Optical Add/Drop Multiplexers (ROADMs) for nodal degree = 2, Photonic Crossconnects (PXCs) for nodal degree >2.



Reduced capital costs
Flexible upgrades
Fast dynamic provisioning
Photonic-layer route diversity

But what about network management functions?

- *Performance monitoring*
- *Fault sectionalization*
- *Path trace*

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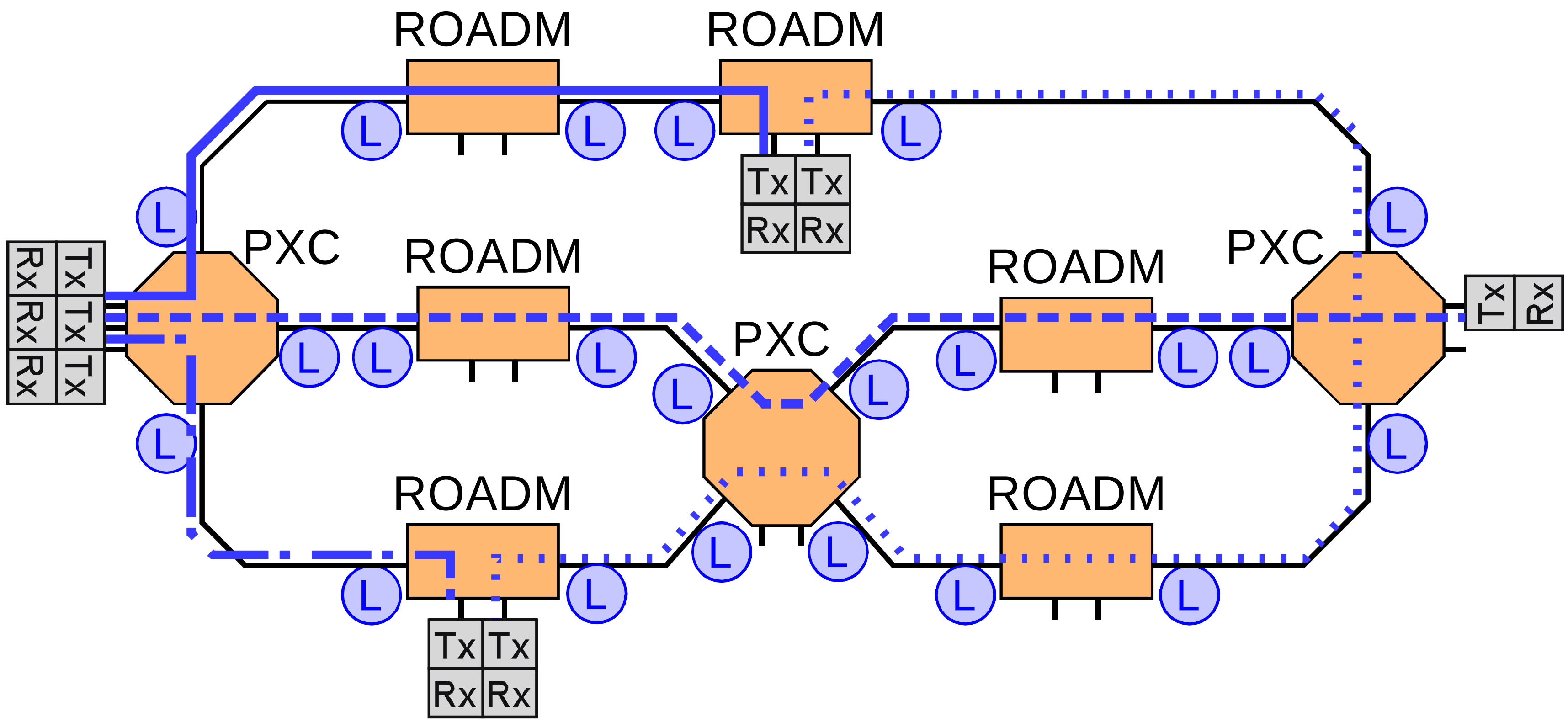
Photonic Path Trace



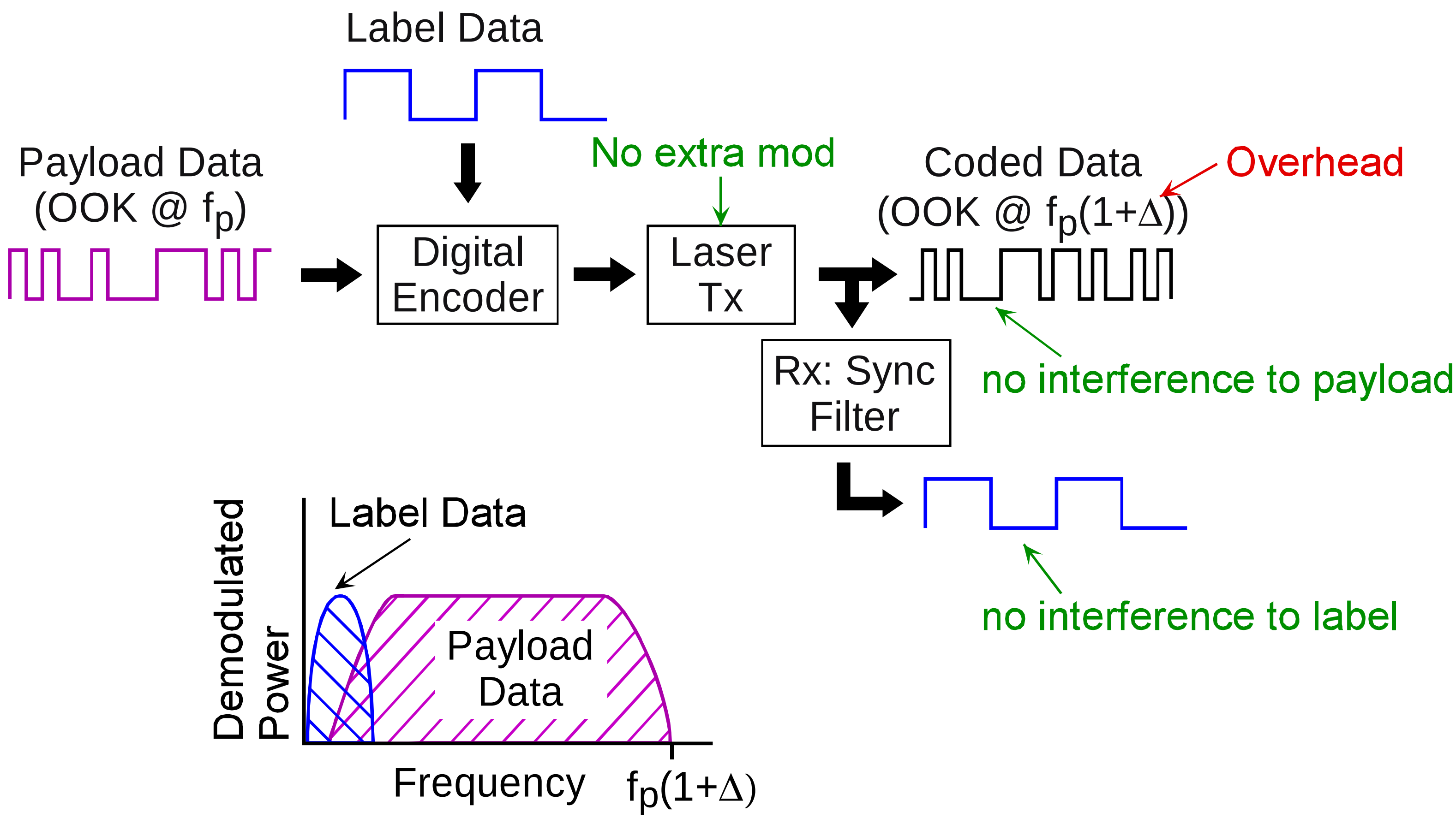
If a wavelength is routed to the wrong destination, which node is at fault?

Lightpaths labeled at source node.

Ubiquitous path trace receivers diagnose and locate faults. (L)

Low cost => no wavelength filter, moderate-speed elex, low optical power

Asymmetric Digital Coding - LightLabel



Moderate f mitigates EDFA xtalk

No new devices required

Versatile message channel @ ~10^3-10^5 b/s per λ

Payload privacy

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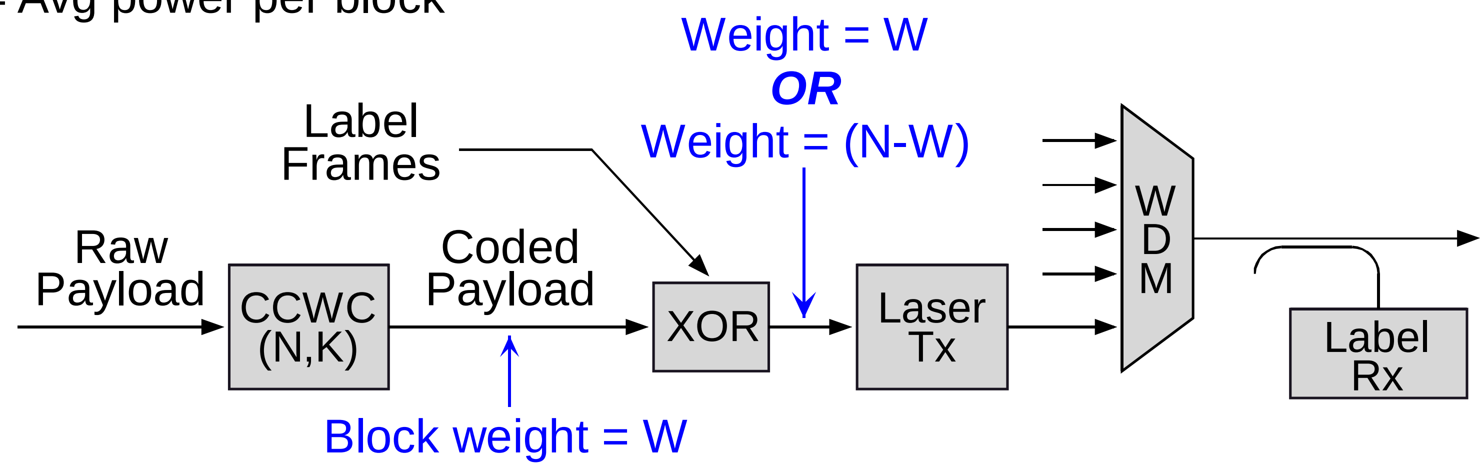
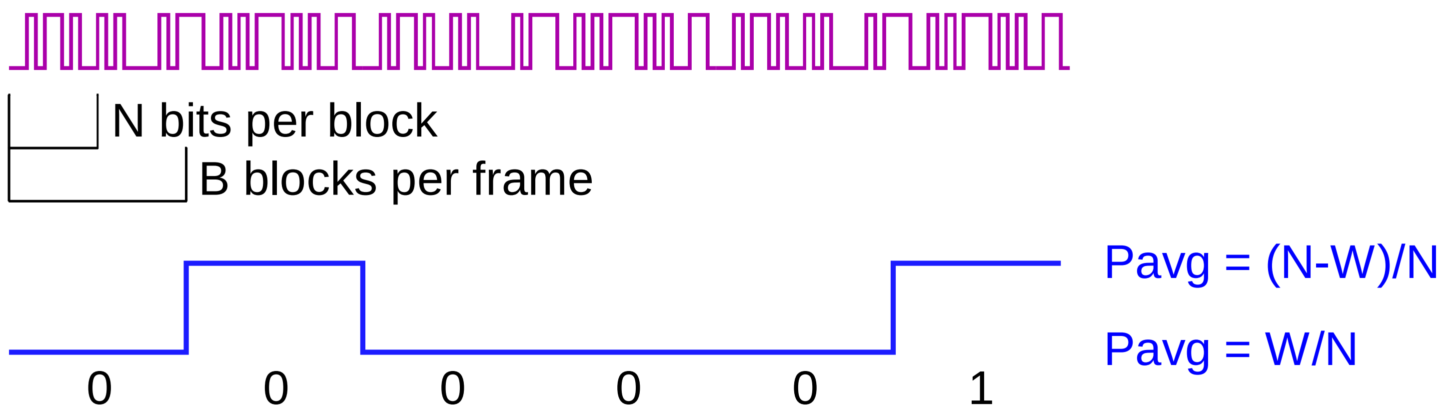
LightLabel Encoding - CCWC

Block coding: each group of K payload bits chooses a code block of length N bits (N>K)

CCWC = Complementary Constant Weight Codes

W/N = Avg power per block

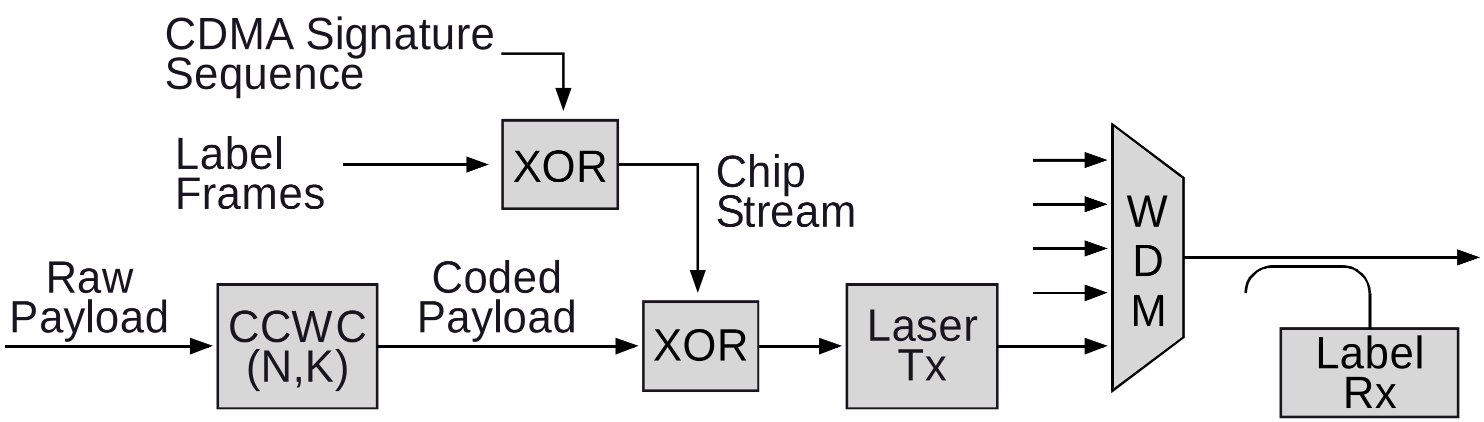




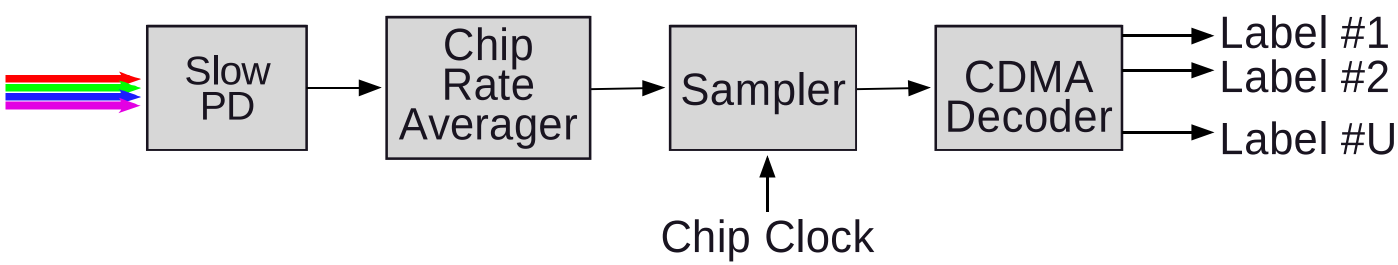
Average power of blocks follows 0/1 values of label frames

LightLabel Encoding - CDMA

- Shared label receiver demands a multiple access strategy => CDMA
- CDMA signature sequence spreads each label frame in time
- One signature per wavelength, label carried as message



Label Rx:



CDMA addresses challenges of noise and multi-user interference

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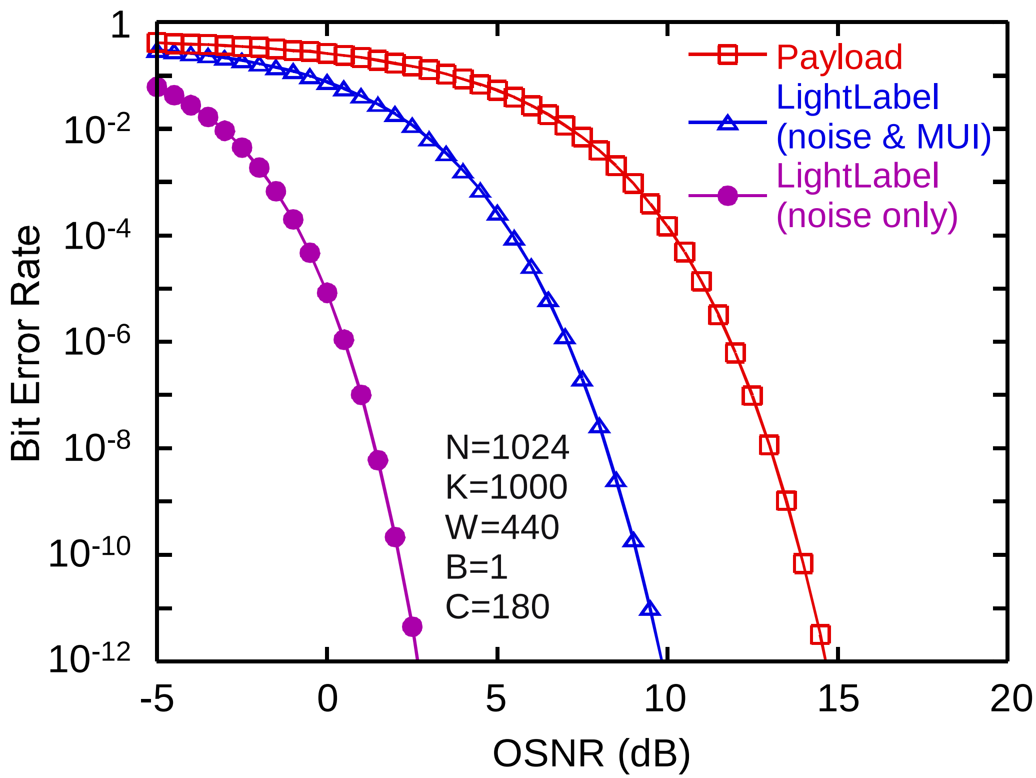
Error Rates vs. OSNR



80 λs
Raw payload @ 10.0 Gb/s (per λ)
Chip rate =10.0 Mb/s
Overhead {(N-K)/K} = 2.4%
Label rate = 55.6 kb/s per λ

Φ = 1 mW, R = 100A/W,
L = .01, B_o = 50 GHz,
σ^c = 0.2 nA/(Hz)$^{1/2}$

Label BER < payload BER
even in the presence of ASE noise and MUI.

M.D. Feuer and V.A. Vaishampayan, paper Tu3.6.3, ECOC2004

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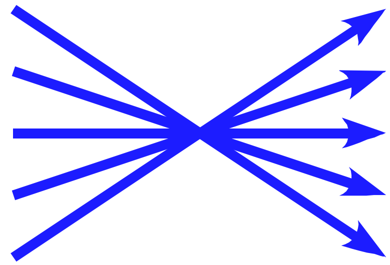
Code Design Choices

K (input bits per block)
N (coded bits per block)
W (weight of block)
B (blocks per chip)
C (signature length)



Chip cost/latency
Label data rate
Chip rate
Overhead
Noise rejection
MUI rejection (max λs: U)

Examples:
Large N increases chip cost/latency, but reduces overhead and improves noise rejection
As W approaches N/2, overhead is reduced but so is noise rejection
Large C reduces MUI penalty but decreases label data rate; must have C>2U
... etc.

Require label E.R. ≤ payload E.R. at all OSNR; compute overhead and label data rate

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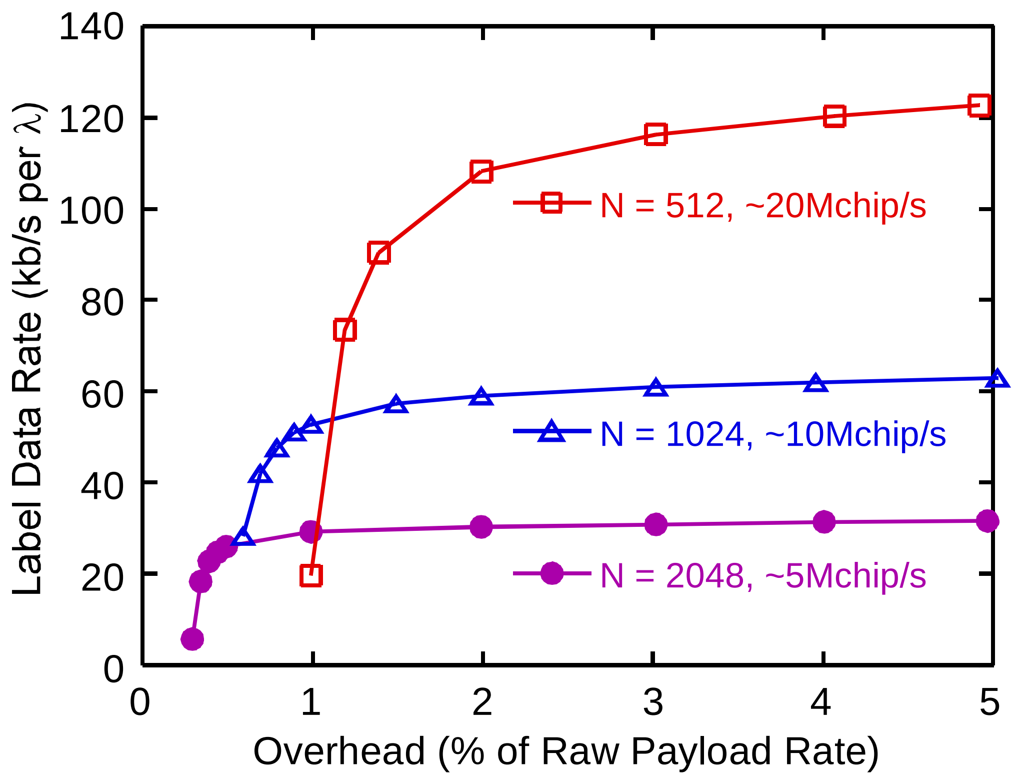
Code Parameters - Overhead

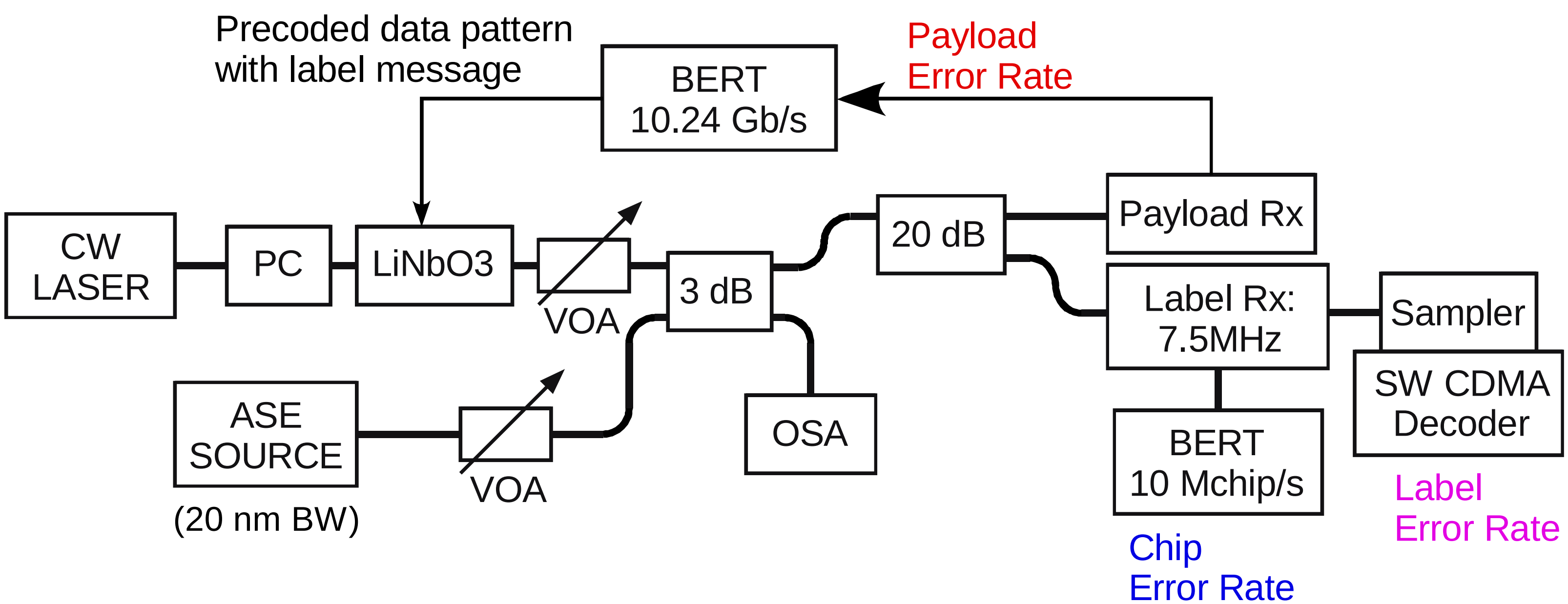


80 λs
Raw payload @ 10.0 Gb/s (per λ)
B=1
(1) Choose K to set overhead
(2) Minimize W
(3) Lower C until BER=1e-9
@ OSNR=12dB

Overhead of 1-2% is enough
Aggregate label data rate (all 80 λs) up to ½ chip rate

Single-User Experiments

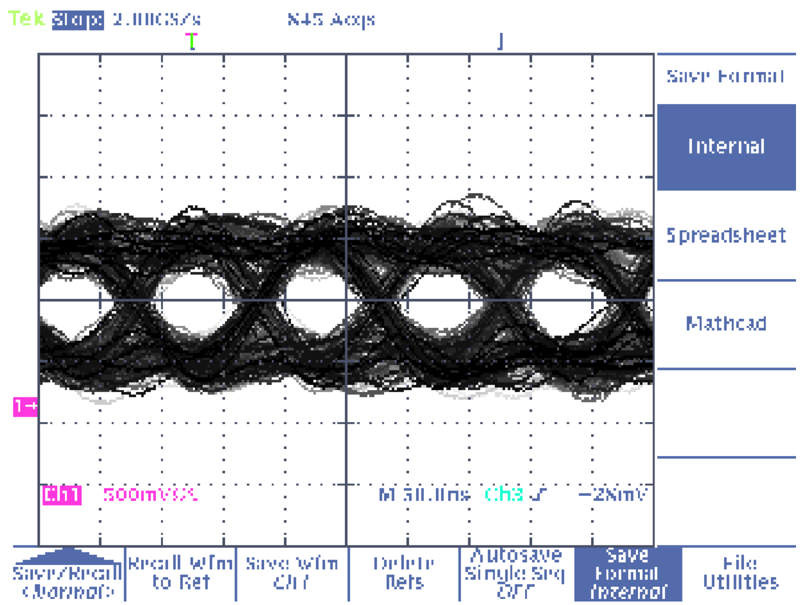
Single channel with variable OSNR
Precalculate encoding and load into BERT pattern
Measure payload, chip error rates
Capture samples and decode in software for label error rate



K=1000, N=1024, B=1, W=440, C=200
10.0 Gb/s raw payload rate, 2.4% overhead
4,000,000 PRBS bits => 4,096,000 coded bits <=> 4000 chips
<=> 20 label frames

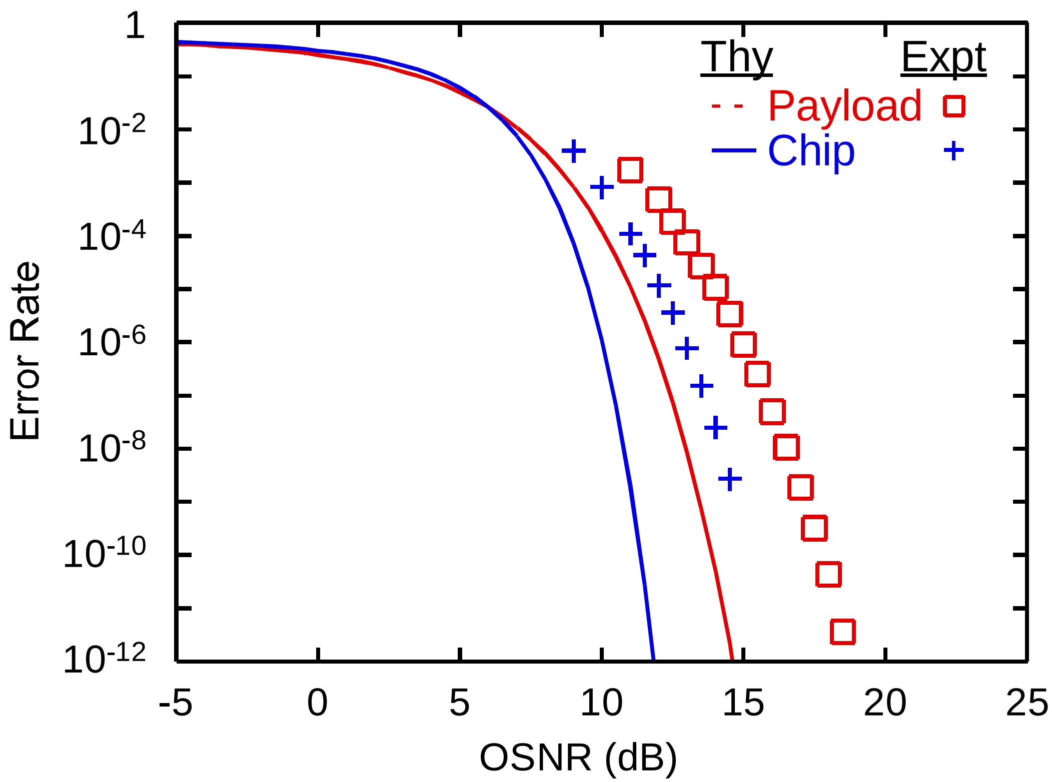
Chip-Level Eye

ASE source OFF



Significant eye closure due to analog filter
(allows xtalk from coded payload)

Chip-Level Error Rate (Single User)



1 λ, 20 nm ASE
Raw payload @ 10.0 Gb/s
Chip rate =10.0 Mb/s
Overhead {(N-K)/K} = 2.4%

Theory has no adjustable params;
assumes ideal integrate-and-dump filter

Low-speed Rx successfully extracts CCWC-coded aux channel
For single user, aux channel rate of 10 Mchips/s is possible.

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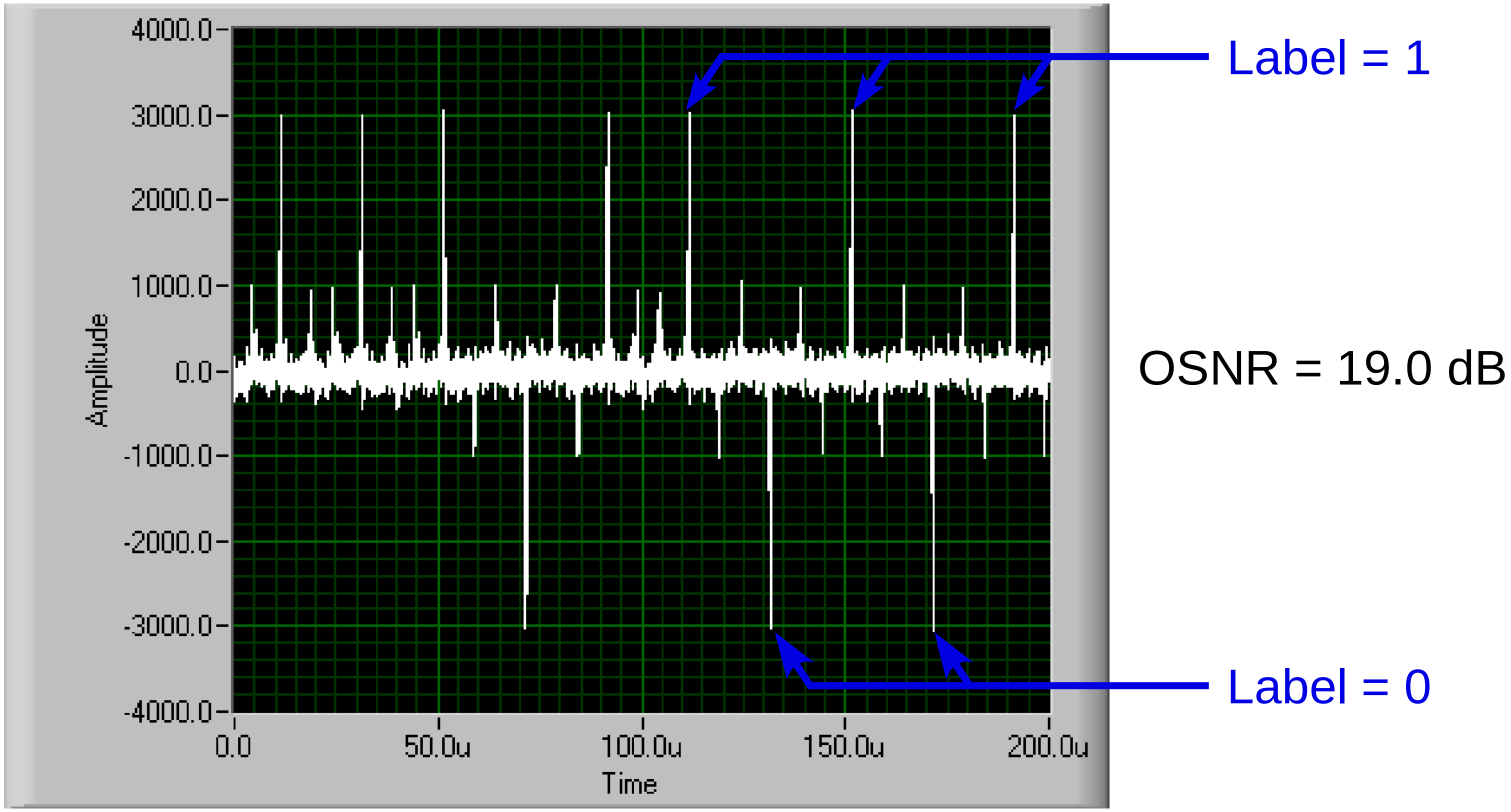
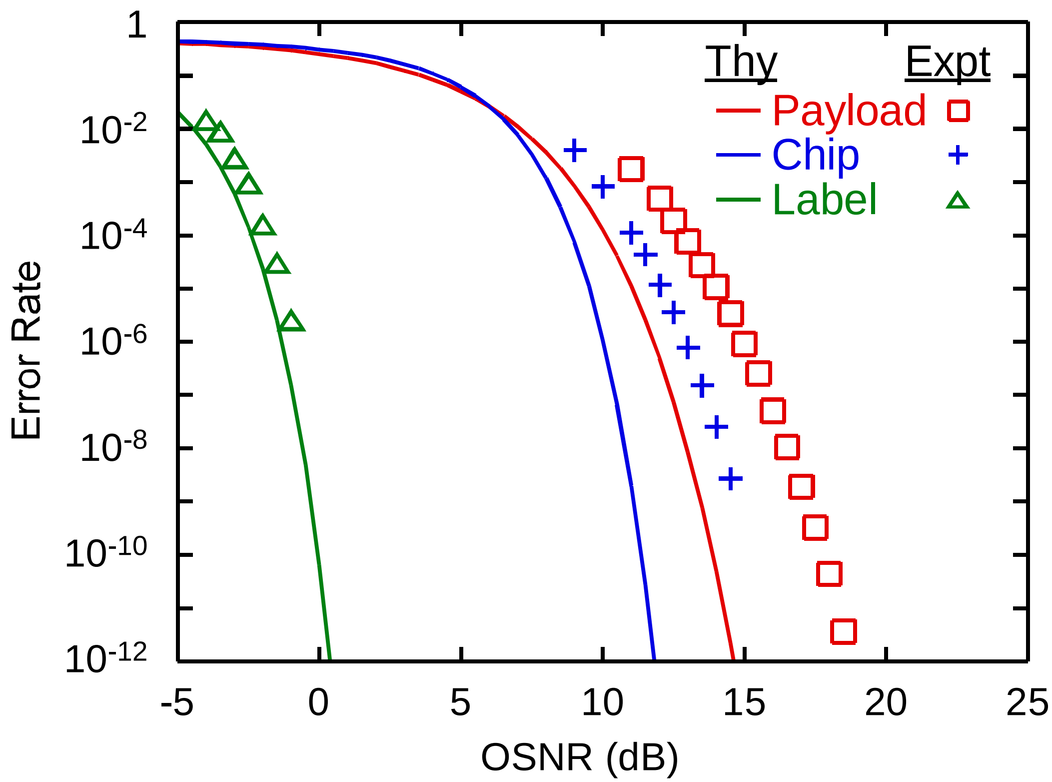
Software Decoder

1.) Capture 50k samples at 5 samples/chip (50MSa/s)
2.) Random capture timing (i.e., no frame trigger)
3.) Correlate with signature sequence to find timing



4.) Extract clocked samples, threshold to make decisions on label data frames

Label Error Rate (Single User)

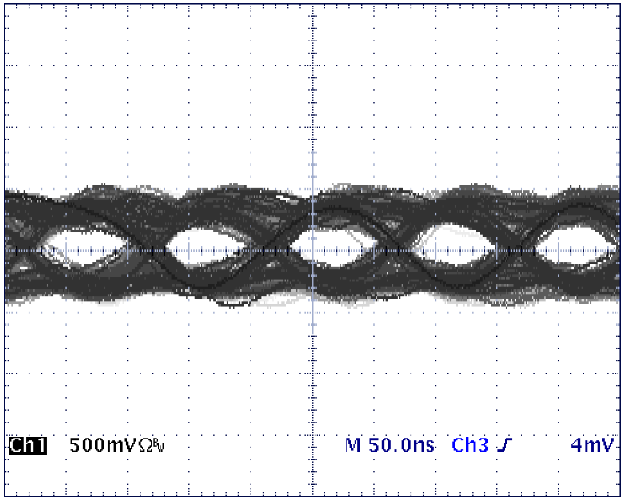


1 λ, 20 nm ASE
Raw payload @ 10.0 Gb/s
Chip rate =10.0 Mb/s
Overhead {(N-K)/K} = 2.4%
Label rate = 50 kb/s

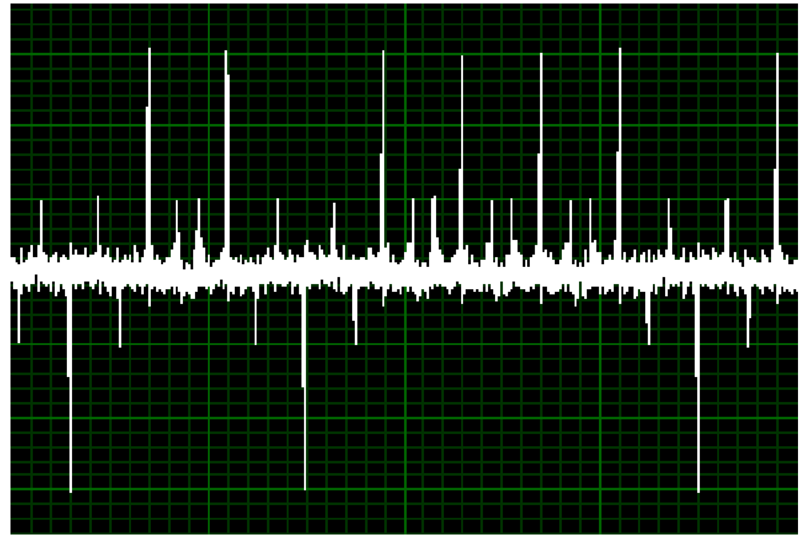
No penalty in label because software decoder uses (clocked) digital filter

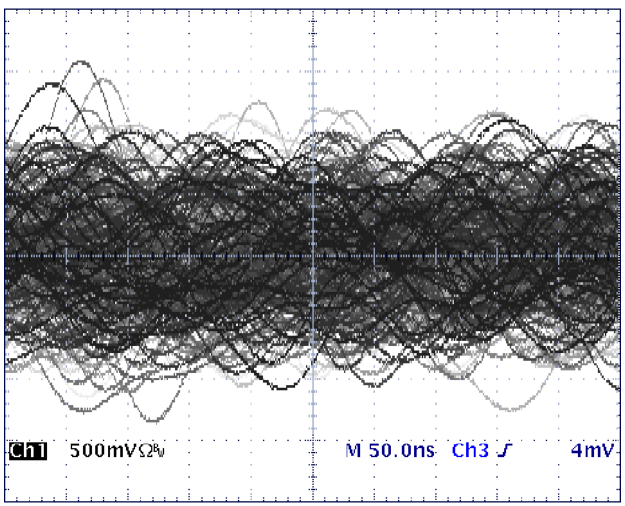
Label BER tolerates 11-12 dB more noise than chip BER

CDMA Noise Rejection

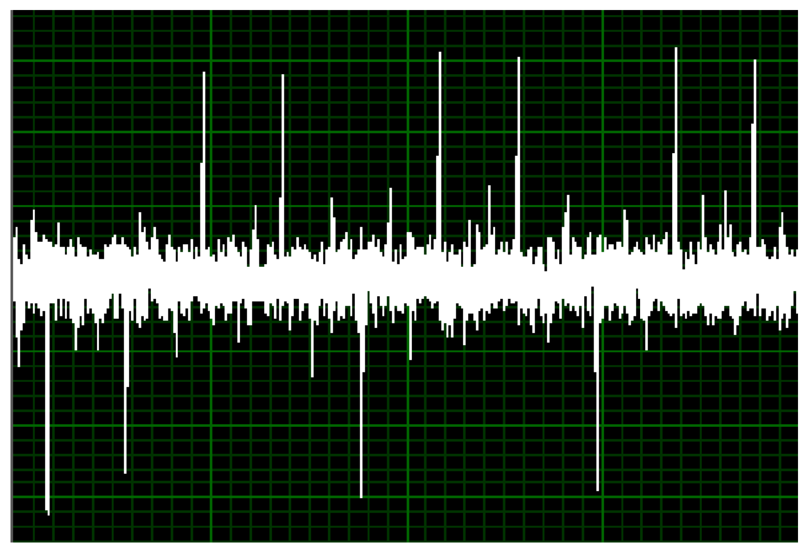


OSNR =
19.0 dB





OSNR =
3.9 dB

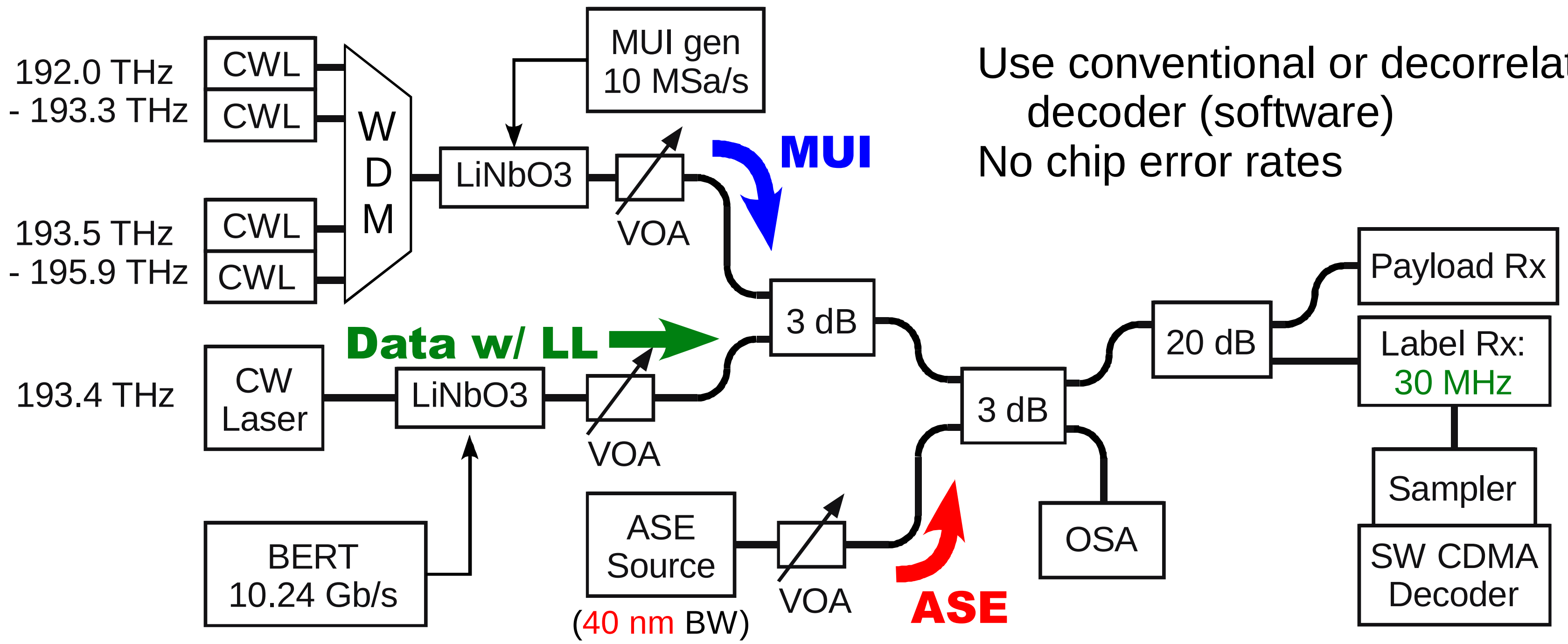


Note that CDMA 'filter' has effective BW of 40kHz

Multi-user Experiments

Add MUI branch:

- 1-39 λ (U = 2 - 40), 100 Ghz spacing
- common mod with aggregate MUI chip stream (200 kchips @10Mchip/s)
- random signatures & frame timing; synchronous chips
- per-chan power = P_{sig} (U = 2 - 40) or P_{sig} + 3 dB (U = 80)



Use conventional or decorrelating decoder (software)
No chip error rates

same code params as single-user:
K=1000, N=1024, B=1, W=440, C=200
10.0 Gb/s raw payload rate, 2.4% overhead

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Multi-User Error Rates - Conventional Decoder

Conventional decoder projects vector of received samples onto CDMA signature sequence

Label error rate vs. OSNR for various wavelength counts
Data not yet released for publication

Conventional decoder OK up to U = 16, but error floors at U = 40, 80.

Multi-User Error Rates - Decorrelating Decoder

Decorrelating decoder projects received samples onto decorrelating vector, chosen orthogonal to all interferers

Label error rate vs. OSNR for various wavelength counts
Data not yet released for publication

Decorrelating decoder extends capability to U = 80.

LightLabel Summary

- Photonic networks demand new management techniques, such as photonic path trace.
- Lightpath labeling with ubiquitous label receivers provides precise tracing of lightpaths.
- LightLabel is a lightpath labeling technique using all-digital encoding (CCWC + CDMA), for high accuracy and versatility at low cost.
- Theory shows and experiments confirm (label BER) < (payload BER) for realistic OSNR and full MUI load.
- Future work: chip-asynchronous operation
effects of dispersion & fiber non-linearities
optimized signature sequences
interworking with FEC

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