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 (PXC) for nodal degree >2.

\[ R = \text{ROADM} \]
\[ P = \text{PXC} \]
\[ E = \text{Elec Switch/IP Router} \]

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

But what about network management functions?
- Performance monitoring
- Fault sectionalization
- 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.

Low cost => no wavelength filter, moderate-speed elex, low optical power.
Asymmetric Digital Coding - LightLabel

Payload Data (OOK @ \( f_p \))

Digital Encoder

No extra mod

Coded Data (OOK @ \( f_p(1+\Delta) \))

Laser Tx

Rx: Sync Filter

Label Data

Demodulated Power

Label Data

Payload Data

Frequency \( f_p(1+\Delta) \)

Moderate \( f \) mitigates EDFA xtalk
No new devices required
Versatile message channel @ \( \sim 10^3-10^5 \) b/s per \( \lambda \)
Payload privacy
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

\[
P_{avg} = \frac{W}{N}
\]

0 0 0 0 0 1

Weight = W  \text{ OR }  Weight = (N-W)

W/D/M

Label Rx

Raw Payload → CCWC (N,K) → Coded Payload

Label Frames

XOR

Block weight = W

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

P_{avg} = \frac{(N-W)}{N}
P_{avg} = \frac{W}{N}

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

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**Label Rx:**

CDMA addresses challenges of noise and multi-user interference
**Error Rates vs. OSNR**

![Graph showing error rates vs. OSNR with markers for Payload, LightLabel (noise only), and LightLabel (noise & MUI).]

- **OSNR (dB)**
  - -5 5 10 20 30
  - 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2}

- **Parameters**
  - N=1024
  - K=1000
  - W=440
  - B=1
  - C=180

- **Remarks**
  - 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

- **Equations**
  - \( \Phi = 1 \text{ mW}, \ R = 100\text{ A/W}, \)
  - \( L = .01, \ B_0 = 50 \text{ GHz}, \)
  - \( \sigma_c = 0.2 \text{ nA/(Hz)}^{1/2} \)

- **Conclusion**
  - 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
**Code Design Choices**

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

<table>
<thead>
<tr>
<th>Chip cost/latency</th>
<th>Label data rate</th>
<th>Chip rate</th>
<th>Overhead</th>
<th>Noise rejection</th>
<th>MUI rejection (max $\lambda$ s: U)</th>
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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. $\leq$ payload E.R. at all OSNR; compute overhead and label data rate*
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)

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.

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

**Graphical Data:**
- **Label = 1**
- **Label = 0**
- **OSNR = 19.0 dB**
Label Error Rate (Single User)

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

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

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
**CDMA Noise Rejection**

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
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.