Project: IEEE P802.15 Working Group for Wireless Personal Area Networks

Submission Title: [Samsung PHY proposal to 802.15.7]
Date Submitted: [22th September, 2009]
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Re: []

Abstract: Samsung PHY proposal for 802.15.7 is described in this document.

Purpose: To trigger discussion and initiate merger with other group members of TG 7.

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Samsung PHY proposal to
IEEE 802.15.7

Samsung Electronics
22th September
Contents

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• Proposal Scope
• Physical Layer Proposal
  – Block Diagram
  – Multiple Preamble
  – Channel Assignment
  – Line Coding
    • 8B10B
  – Modulation
    • CCM(Color Code Modulation)
    • HHW(High Hamming Weight)

• Reference
TCD (Technical Consideration Document)

- PHY considerations based on Current TCD
  - Data rate
    - data rate: 6.4Mbps~96Mbps
  - Distance
    - Short range: <= 3m
  - Device characteristic of light source
    - Divergence angle: 10 degree ~ 30 degree
  - Visibility support
Proposal scope

• P2P (Peer to Peer)
  – Full duplex (with visibility)
  – Data rate: 96Mbps

• Visible LAN
  – TDD Half duplex
  – Distance: 3m
  – Data rate: 6.4Mbps

• Information broadcasting
  – Uni-direction
  – TDD Half duplex
  – Distance: 3m
  – Data rate: 6.4Mbps
Block Diagram
## Proposed data rate

<table>
<thead>
<tr>
<th>Channel Coding (HHW, CC, RS)</th>
<th>Line coding</th>
<th>Sampling frequency</th>
<th>Uncoded data rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/3</td>
<td>0.8 (ex.8B10B)</td>
<td>12</td>
<td>6.4</td>
</tr>
<tr>
<td>1 (No channel coding)</td>
<td>0.8</td>
<td>12</td>
<td>9.6</td>
</tr>
<tr>
<td>2/3</td>
<td>0.8</td>
<td>48</td>
<td>25.6</td>
</tr>
<tr>
<td>1</td>
<td>0.8</td>
<td>48</td>
<td>38.4</td>
</tr>
<tr>
<td>2/3</td>
<td>0.8</td>
<td>96</td>
<td>51.2</td>
</tr>
<tr>
<td>1</td>
<td>0.8</td>
<td>96</td>
<td>76.8</td>
</tr>
<tr>
<td>2/3</td>
<td>0.8</td>
<td>120</td>
<td>64</td>
</tr>
<tr>
<td>1</td>
<td>0.8</td>
<td>120</td>
<td>96</td>
</tr>
</tbody>
</table>
Preamble and PHY header

The information about the application is passed by the upper layers to the MAC. The MAC instructs the PHY to set the preamble for TX and for RX.
Multiple Preamble

- Problem
  - interference from ambient light sources such as sunlight, incandescent and fluorescent lamps, VLC can suffer from three types of network interference:
    - Inter-application interference (same color)
    - Intra-application interference (same color)
    - Adjacent color interference
Multiple Preamble

- Benefits of multiple preamble
  - Since different preambles are used to separate different applications and/or adjacent LAN networks and/or adjacent color channels, the receiver can reject preambles of unwanted transmitters and continue listening until it sees the preamble of the desired transmitter, saving both power and having better probability of acquisition.
Proposed preamble design

• 4 preamble sequences
  – P1 .. P4 : to distinguish applications

• 2 flip patterns per preamble
  – + and – : randomly selected to minimize interference

• 7 Cover sequences for preamble repetitions
  – 7 logical channels to separate different colors
  – Cover sequence also helps identify end of current preamble (end of preamble marker) to tell if next symbol after preamble is data or just another noisy preamble pattern

• Higher distance means less probability of false frame sync. Distances closer to the end of the sequence are more important since the decision at the end of the frame sync sequence is crucial to determining packet detection and the initial parts of the sequence can get lost in AGC and packet detection algorithms.
Proposed preamble design

- Extended preamble for visibility and faster/better synchronization
  - Preambles can also be sent as extended visibility patterns in advance of a packet transmission since they can provide visibility while simultaneously offering a chance for synchronization and additional receiver training for fast association.

(a) Default transmission

(b) Transmit extended preamble for visibility and for faster and better synchronization
## Proposed Band Plan
(based on CIE diagram)

<table>
<thead>
<tr>
<th>Frequency band (nm)</th>
<th>Spectral width (nm)</th>
<th>Color</th>
<th>Proposed Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>380</td>
<td>450</td>
<td>pB</td>
<td>000</td>
</tr>
<tr>
<td>450</td>
<td>510</td>
<td>B, BG</td>
<td>001</td>
</tr>
<tr>
<td>510</td>
<td>560</td>
<td>G</td>
<td>010</td>
</tr>
<tr>
<td>560</td>
<td>600</td>
<td>yG,gY, Y,yO,O</td>
<td>011</td>
</tr>
<tr>
<td>600</td>
<td>650</td>
<td>rO</td>
<td>100</td>
</tr>
<tr>
<td>650</td>
<td>710</td>
<td>R</td>
<td>101</td>
</tr>
<tr>
<td>710</td>
<td>780</td>
<td>R</td>
<td>110</td>
</tr>
<tr>
<td>Reserved</td>
<td></td>
<td></td>
<td>111</td>
</tr>
</tbody>
</table>

- Non-uniform distribution based on CIE diagram
- Human eye most sensitive to green color and visible LEDs are designed to match human eye sensitivity
- Provides support for up to 7 independent and parallel channels – can consider expansion to more channels

Red – popular LED for comm.

Ying Li, Samsung Electronics
Need for guard colors

• Many LEDs (such as white) may not support saturated colors and may transmit in multiple bands
  - Spectrum affected by leakage may be unusable
• For FDD mode, adjacent bands may be impacted by spectral leakage from own transmitter
• Significant variations in LED spectral width and peak wavelengths for different manufacturers and costs
• LED peak wavelength can change with forward current variations.
Guard colors

- Define “guard color” channels for each channel used for transmissions.

- For every channel color, we define a list of guard colors that cannot be used simultaneously for TX or RX when that channel is in use for TX due to leakage.
  - For example, white led (blue + phosphor) Color code : 001 Guard codes : 011, 100

- The criteria used for defining a guard color channel could be based on out-of-band leakage, exceeding a certain value (for example, 10 -20 dB) over the in-channel value that causes a considerable loss in receiver sensitivity in those channels.

- The guard colors are defined on a per channel basis and could be also be defined as a N-bit number with a ‘1’ in the location where the channel cannot be used.
Coding scheme for VLC

• Line coding
  – 8B10B

• Channel coding (Under investigation)
  – HHW
  – CC
  – RS

• CCM (Optional for multi color support)
  – 4CCM, 8CCM, 16CCM
Line Coding

- **8B10B**
  - The 8B/10B line code that converts 8-bit to 10-bit is used in this proposal. It can help to acquire DC-balance, disparity, and clock recovery by enough state changes. It is specified in ANSI/INCITS 373: Fibre Channel Framing and Signaling Interface (FC-FS), Clause 11
Line Coding - 8B10B

- Features
  - DC balanced line code
  - Combination of 3B4B and 5B6B encoding
  - Error detection capability
  - Run length is limited to 5.
  - Disparities are constrained to be -2, 0, 2.
  - 3B4B encoding (bottom)
  - 5B6B encoding (right)

- Example

<table>
<thead>
<tr>
<th>(RD-)</th>
<th>D20.7</th>
<th>(RD+)</th>
<th>D7.1</th>
<th>(RD+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Violation</td>
<td>(RD-)</td>
<td>001011 0111</td>
<td>(RD+)</td>
<td>111000 1001</td>
</tr>
<tr>
<td>Correct</td>
<td>(RD-)</td>
<td>001011 0111</td>
<td>(RD+)</td>
<td>000111 1001</td>
</tr>
</tbody>
</table>
Modulation - What is CCM?

- Data train is coded in the xy color coordinate.
- xy values are transformed into RGB values.
- The relation between xy and RGB is showed by following equations . (R:700nm, G:546.1nm, B:435.8nm)

\[ X = 2.7689R + 1.7517G + 1.1302B \]
\[ Y = R + 4.5907G + 0.0601B \]
\[ Z = 0.0565G + 5.5943B \]
\[ x = X / (X + Y + Z) \]
\[ y = Y / (X + Y + Z) \]

- CCM symbols are provided as the visible colors which are made by RGB light sources.
- The information is transmitted as the intensity ratio among RGB.
PHY header for CCM

<table>
<thead>
<tr>
<th>Preamble</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>P2P</td>
</tr>
<tr>
<td>P2</td>
<td>VLAN</td>
</tr>
<tr>
<td>P3</td>
<td>IB</td>
</tr>
<tr>
<td>P4</td>
<td>VB</td>
</tr>
</tbody>
</table>

** PHY header fields **

<table>
<thead>
<tr>
<th>Explanation on use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduce preamble and IFS</td>
</tr>
</tbody>
</table>

** Burst mode **

** Preamble **

** Channel number **

** Data rate **

** Length of MAC payload **

** Optional Mode **

<table>
<thead>
<tr>
<th>Reserved fields</th>
</tr>
</thead>
<tbody>
<tr>
<td>For future extension</td>
</tr>
</tbody>
</table>

CE Sequence: 15 walsh code symbols
## Proposed data rate for CCM mode

<table>
<thead>
<tr>
<th>Channel coding</th>
<th>CCM type</th>
<th>Sampling Frequency 4x</th>
<th>Uncoded data rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/3</td>
<td>4 CCM</td>
<td>24</td>
<td>8</td>
</tr>
<tr>
<td>1</td>
<td>4 CCM</td>
<td>24</td>
<td>12</td>
</tr>
<tr>
<td>(No channel coding)</td>
<td>4 CCM</td>
<td>24</td>
<td>12</td>
</tr>
<tr>
<td>2/3</td>
<td>8 CCM</td>
<td>48</td>
<td>24</td>
</tr>
<tr>
<td>1</td>
<td>8 CCM</td>
<td>48</td>
<td>36</td>
</tr>
<tr>
<td>2/3</td>
<td>8 CCM</td>
<td>96</td>
<td>48</td>
</tr>
<tr>
<td>1</td>
<td>8 CCM</td>
<td>96</td>
<td>72</td>
</tr>
<tr>
<td>2/3</td>
<td>16 CCM</td>
<td>96</td>
<td>64</td>
</tr>
<tr>
<td>1</td>
<td>16 CCM</td>
<td>96</td>
<td>96</td>
</tr>
</tbody>
</table>
Why CCM?

- **WDM (RGB 3 colors)**
  - Transmit data is distributed to RGB channels
  - The channels are decided by the wave length
  → The connectivity is depend on Light Devices (LED, PD)!

- **CCM**
  - Transmit data is allocated in the color coordinate plane.
  - The channels are decided by mixed color of RGB.
  → The connectivity is guaranteed symbol allocation on the xy color coordinate!
CCM symbol allocations

8 CCM
(3bits/Symbol)

16 CCM
(4bits/Symbol)

64 CCM
(6bits/Symbol)

Symbol positions in xy color coordinate for CCM performance evaluation

- 4CCM (2bits/Symbol) has been shown in previous page.
- Those symbol positions were decided for having same distance from adjacent symbols.
Experimental Results (25MHz/Symbol)

8CCM (75Mbps)  
BER < 10^-7

16CCM (100Mbps)  
BER < 10^-7

64CCM (150Mbps)  
BER ≒ 10^-2
BER performance with random noise

CCM BER vs. SNR (2.5MHz/symbol)
BER performance vs. Bit rate

Data speed performance

- 4CCM
- 8CCM
- 16CCM
- 64CCM

Under 1.E-7
Modulation

• HHW (High Hamming Weight)
  – Motivation
    • In level line code like NRZ, OOK, etc, as the appearance of 1s increases, the illumination of system is improved.
      – Ex) [0 1 1 1 0 1 1 1] → 6/8=0.75
        [0 0 1 0 0 1 0 0] → 2/8=0.25
    • In general, the occurrence of 0 and 1 is equiprobable.
  – We propose coded modulation with high density of 1’s by intentionally using high Hamming weight codewords.
High Hamming Weight (HHW) Coded Modulation

- High Hamming Weight coded modulation
  - HHW channel encoding block
    - High Hamming weight codewords are selected for transmission to improve the illumination
  - Example for HHW encoding: (7,4) Hamming code

<table>
<thead>
<tr>
<th>Message</th>
<th>Codewords</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 0 0 0</td>
<td>0 0 0 0 0 0</td>
<td>Unused</td>
</tr>
<tr>
<td>1 0 0 0</td>
<td>1 1 0 1 0 0</td>
<td>Used</td>
</tr>
<tr>
<td>0 1 0 0</td>
<td>0 1 1 0 1 0</td>
<td>Unused</td>
</tr>
<tr>
<td>1 1 0 0</td>
<td>1 0 1 1 1 0</td>
<td>Used</td>
</tr>
<tr>
<td>0 0 1 0</td>
<td>1 1 0 0 1 0</td>
<td>Used</td>
</tr>
<tr>
<td>1 0 1 0</td>
<td>0 1 1 0 1 0</td>
<td>Unused</td>
</tr>
<tr>
<td>0 1 1 0</td>
<td>1 0 0 1 1 0</td>
<td>Unused</td>
</tr>
<tr>
<td>1 1 1 0</td>
<td>0 1 0 1 1 0</td>
<td>Used</td>
</tr>
<tr>
<td>0 0 0 1</td>
<td>1 0 1 0 0 1</td>
<td>Unused</td>
</tr>
<tr>
<td>1 0 0 1</td>
<td>0 1 1 0 0 1</td>
<td>Used</td>
</tr>
<tr>
<td>0 1 0 1</td>
<td>1 1 0 1 0 1</td>
<td>Used</td>
</tr>
<tr>
<td>1 1 0 1</td>
<td>0 0 1 1 0 1</td>
<td>Unused</td>
</tr>
<tr>
<td>0 0 1 1</td>
<td>0 1 0 0 1 1</td>
<td>Unused</td>
</tr>
<tr>
<td>1 0 1 1</td>
<td>1 0 0 1 1 1</td>
<td>Used</td>
</tr>
<tr>
<td>0 1 1 1</td>
<td>0 0 1 0 1 1</td>
<td>Unused</td>
</tr>
<tr>
<td>1 1 1 1</td>
<td>1 1 1 1 1 1</td>
<td>Used</td>
</tr>
</tbody>
</table>
Simulation parameter set-ups

- Same peak power constraint
  - LED has a peak power limit. Maximum current of existing LEDs is strictly regulated. The peak current indicates magnitude of load on the LED.
  → Thus, we made the simulations to see the performance of various modulation schemes under the condition that peak power i.e., amplitude of each modulation is equal.
- Data rate: 10 Mbps
- Modulation and Coding scheme

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Coding</th>
</tr>
</thead>
<tbody>
<tr>
<td>OOK</td>
<td>No coding</td>
</tr>
<tr>
<td>OOK</td>
<td>Convolutional coding (R=1/2, K=7)</td>
</tr>
<tr>
<td>8B10B</td>
<td>No coding</td>
</tr>
<tr>
<td>8B10B</td>
<td>Convolutional coding (R=1/2, K=7)</td>
</tr>
<tr>
<td>HHW Reed Muller coded modulation</td>
<td>OOK + Reed Muller coding (R=1/2, (16,32) code)</td>
</tr>
<tr>
<td>HHW CC coded modulation</td>
<td>OOK + CC (R=1/2, K=7)</td>
</tr>
</tbody>
</table>

HHW BER Performance

- 8B10B and No coding
- 8B10B and Convolutional coding
- OOK and No coding
- OOK and Convolutional coding
- HHW (RM)
- I-4-PPM

Constraint length : 7
Coding rate: 1/2
Performance Comparisons

- Average optical power normalized to peak power

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Average Optical Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>OOK</td>
<td>0.5</td>
</tr>
<tr>
<td>OOK+CC</td>
<td>0.5</td>
</tr>
<tr>
<td>I-4-PPM</td>
<td>0.75</td>
</tr>
<tr>
<td>8B10B</td>
<td>0.5</td>
</tr>
<tr>
<td>8B10B+CC</td>
<td>0.5</td>
</tr>
<tr>
<td>HHW RM coded modulation</td>
<td>0.558</td>
</tr>
<tr>
<td>HHW CC coded modulation</td>
<td>0.505</td>
</tr>
</tbody>
</table>

- BER performance with channel coding
  - HHW RM, 8B10B+CC > I-4PPM
Reference


Appendix
Multiple Preamble

• Problem
  – It is possible that there may be leakage from adjacent color bands into the band of the chosen color, causing adjacent color interference.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Wavelength band (nm)</th>
<th>Spectral width (nm)</th>
<th>Color from CIE diagram</th>
<th>Proposed Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>c1</td>
<td>380 450</td>
<td>70</td>
<td>pB</td>
<td>000</td>
</tr>
<tr>
<td>c2</td>
<td>450 510</td>
<td>60</td>
<td>B, BG</td>
<td>001</td>
</tr>
<tr>
<td>c3</td>
<td>510 560</td>
<td>50</td>
<td>G</td>
<td>010</td>
</tr>
<tr>
<td>c4</td>
<td>560 600</td>
<td>40</td>
<td>yG,gY, Y,yO,O</td>
<td>011</td>
</tr>
<tr>
<td>c5</td>
<td>600 650</td>
<td>50</td>
<td>rO</td>
<td>100</td>
</tr>
<tr>
<td>c6</td>
<td>650 710</td>
<td>60</td>
<td>R</td>
<td>101</td>
</tr>
<tr>
<td>c7</td>
<td>710 780</td>
<td>70</td>
<td>R</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td>Reserved</td>
<td></td>
<td></td>
<td>111</td>
</tr>
</tbody>
</table>
Multiple Preamble

- Different preambles are used to separate different applications

<table>
<thead>
<tr>
<th>Preamble</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>P2P</td>
</tr>
<tr>
<td>P2</td>
<td>VLAN</td>
</tr>
<tr>
<td>P3</td>
<td>IB</td>
</tr>
<tr>
<td>P4</td>
<td>VB</td>
</tr>
</tbody>
</table>

P1: 1 1 1 1 0 1 0 1 1 0 0 1 0 0 0
P2: 0 0 1 0 1 1 1 0 1 1 1 1 1 1 0
P3: 1 0 0 1 1 0 0 0 0 1 0 0 1 1 1
P4: 0 1 0 0 0 0 1 1 0 1 0 0 1 0 1
Proposed preamble design

• Cover sequence
  – cover sequences are to be applied only to the end of the preamble repetition pattern. For example, if the preamble is being repeated 32 times, the cover sequences proposed is only applied on the last 8 repetitions.

<table>
<thead>
<tr>
<th>Cover sequence</th>
<th>Distances</th>
<th>Sum</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1: 0 0 0 1 0 1 0 1</td>
<td>5 1 4 1 2 1 1</td>
<td>15</td>
<td>7.79</td>
</tr>
<tr>
<td>C2: 0 0 1 0 0 1 0 1</td>
<td>5 3 1 3 1 1 1</td>
<td>15</td>
<td>8.09</td>
</tr>
<tr>
<td>C3: 0 0 1 0 1 0 0 1</td>
<td>5 3 2 3 0 1 1</td>
<td>15</td>
<td>8.23</td>
</tr>
<tr>
<td>C4: 0 0 1 0 1 0 1 0</td>
<td>6 1 4 1 2 1 0</td>
<td>15</td>
<td>8.65</td>
</tr>
<tr>
<td>C5: 0 1 0 0 1 0 1 0</td>
<td>6 2 2 3 0 2 0</td>
<td>15</td>
<td>8.75</td>
</tr>
<tr>
<td>C6: 0 1 0 1 0 0 1 0</td>
<td>6 2 2 3 0 2 0</td>
<td>15</td>
<td>8.75</td>
</tr>
<tr>
<td>C7: 0 1 0 1 0 1 0 1</td>
<td>7 0 5 0 3 0 1</td>
<td>16</td>
<td>9.41</td>
</tr>
</tbody>
</table>
Multiple Preamble

• “flipped” preamble patterns to distinguish within an application type (intra-application separation).
  – by looking at the sign of the received correlation, a determination can be made whether the sequence or its inverted pattern was transmitted

<table>
<thead>
<tr>
<th>Preamble</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1, ~P1</td>
<td>P2P</td>
</tr>
<tr>
<td>P2, ~P2</td>
<td>VLAN</td>
</tr>
<tr>
<td>P3, ~P3</td>
<td>IB</td>
</tr>
<tr>
<td>P4, ~P4</td>
<td>VB</td>
</tr>
</tbody>
</table>
Preamble simulation results

Cross-correlation for Sequence Number: 1

Cross-correlation for Sequence Number: 2

Cross-correlation for Sequence Number: 3

Cross-correlation for Sequence Number: 4
Band plan design for communicating supported channels

Notes from CIE diagram

- Center colors are narrower in width than outer colors.
- Human eye is more sensitive to center colors.
- pB, R occupy 100~200 nm while G occupies ~ 30 nm.
- LED manufacturers make LEDs depending on human color perception and not frequency band.

=> Non-linear widths needed for band plan.
Human eye response to wavelength

Response of Human Eye Versus Wavelength
(Data from the 1988 C.I.E. Photopic Luminous Efficiency Function)
Bandplan issue:
Leakage from other LED colors

Source: http://www.theledlight.com/technical3.html
White LED spectrum (Blue + Phosphor)

Blue LED (GaInN)

Light sensitivity to human eye

Yellow Phosphor – yttrium aluminum garnet (YAG) – leakage if not used at RX

Source: Maxim, Application Note 3070: Standard and White LED Basics and Operation
# CCM Performance Table

<table>
<thead>
<tr>
<th>Symbol Rate</th>
<th>4CCM 2bit/symbol</th>
<th>8CCM 3bit/symbol</th>
<th>16CCM 4bit/symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>12MHz</td>
<td>24Mbps &lt;10^{-7}</td>
<td>36Mbps &lt;10^{-7}</td>
<td>48Mbps &lt;10^{-7}</td>
</tr>
<tr>
<td>24MHz</td>
<td>72Mbps &lt;10^{-7}</td>
<td>96Mbps &lt;10^{-7}</td>
<td></td>
</tr>
</tbody>
</table>
Why CCM?

• Light source spectrum are different among the various devices.
• CCM symbols are produced by several light sources according to the color coordinate.
• CCM symbols can be reproduced by different light sensors.
• CCM guarantees the connectivity each device with xy color coordinate.
• CCM is better for VLC standardization with considering the connectivity among the different devices.
CCM Low Speed Applications

* Data Speed Estimation
  Symbol Rate: 15Hz
  CCM: 4 bit (16 points)
  SDM: 16x16 points

Applications
- Special Information
- Voice streaming
- Support for disabled person
- Security

Those applications are realized by existing devices and infrastructures.
RGB Calibration

CCM system configuration with RGB calibration

- Ambient light
- RGB imbalance
- RGB interference
- Error on xy coordinate
Effect of RGB Calibration

Before RGB Calibration

After RGB Calibration

RGB Calibration

Demodulated Signal Simbol for CMC before RGB calibration

Demodulated Signal Simbol for CMC with symbol points (datadem)
CCM Experiment

VLC Test Bed configuration
Experimental Results (10MHz/Symbol)

8CCM (30Mbps)  
BER < 10^{-7}

16CCM (40Mbps)  
BER < 10^{-7}

64CCM (60Mbps)  
BER ≒ 10^{-3}
BER performance comparing with WDM

2WDM: 2 levels Wave Division Multiplex (3bits/symbol)  ⇔  8CCM (3bit/symbol)
4WDM: 4 levels Wave Division Multiplex (6bits/symbol)  ⇔  64CCM (6bit/symbol)
Convolutional Coding

- Encoder block
  - Constraint length : 7

- Puncturing pattern \((R = \frac{1}{2})\)
HHW BER Performance

![Graph showing BER performance with various encoding methods.](image)