SubOptic 2007

Enabling Global Communications

Data Coding for Submarine systems

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OUTLINE

- Overview and role of Data Coding
- Modulation Format
- Forward Error Correction codes
- Advanced equalization
- Summary

Definition in Data Coding

Search result of Data Coding in title by IEEE Explore®

- Volume ***data coding*** based on region segmentation using finite mixture model
- Quality preserved image ***data coding*** in angiography migration from cinefilm
- Nonlinear neural prediction in 1D DPCM for efficient image ***data coding***
- Video signal processor (VSP) ULSIs for video ***data coding***
- Segmentation of Multivariate Mixed Data via Lossy ***data coding*** and Compression
- Ground clutter removal and ***data coding*** in radar meteorological maps
- Specialized Video and Physiological ***data coding*** System for Remote Monitoring ………………………………….

- ***Line Code*** Design for High-Capacity Baseband Digital Transmission Systems
- Transmission performance analysis of a new class of ***line codes*** for optical fiber systems
- Sliding-block ***line codes*** to increase dispersion-limited distance of optical fiber channels
- Ghost-pulse reduction in 40-Gb/s systems using ***line coding***

We will discuss "LINE CODING" in this tutorial

Purpose of this tutorial

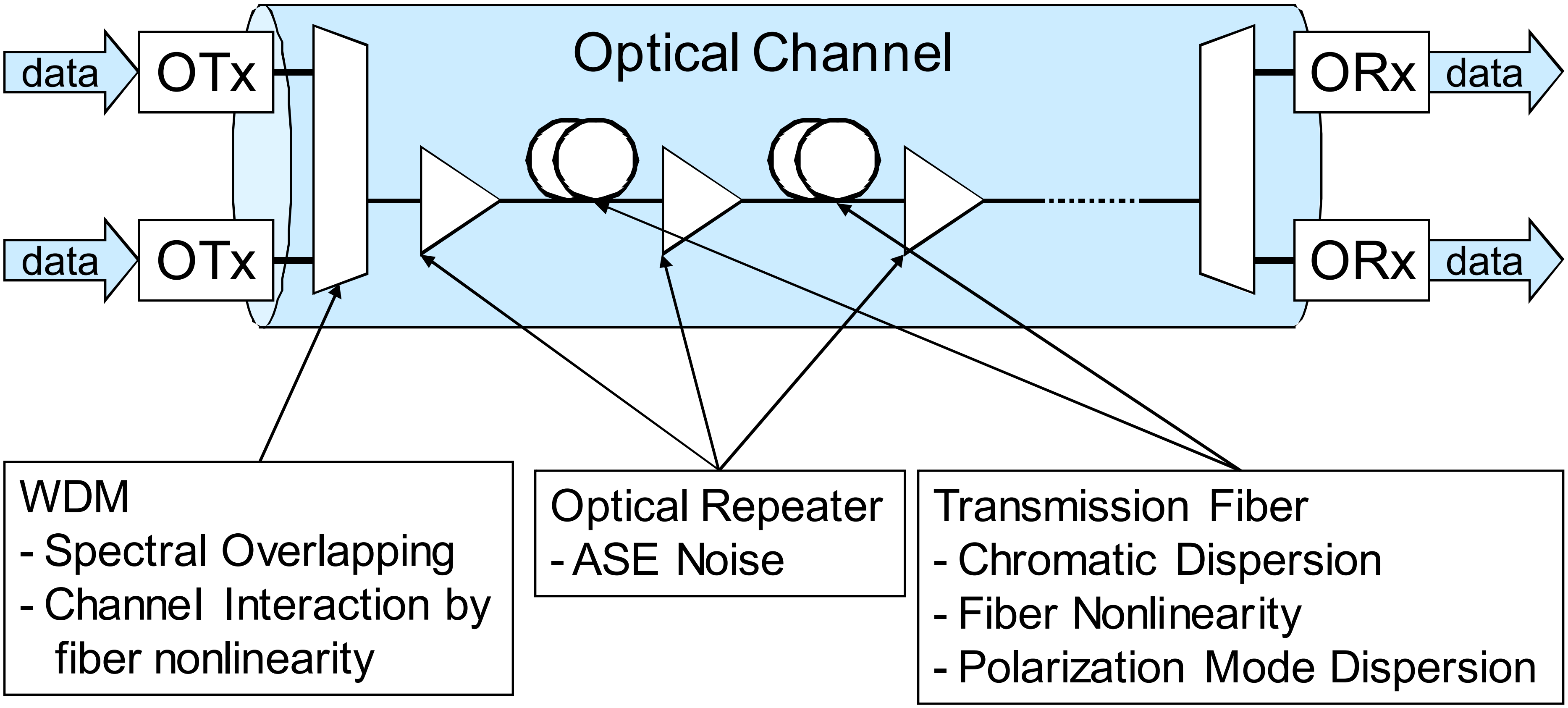
- Review Data Coding related technologies,
  - Modulation format
  - Forward Error Correction
  - Advanced Equalization
- Summarize a recent trend of those technologies in R&D field, especially for submarine systems

Role of Data Coding in Communication

- Maximize performance of the communication under the restricted transmission medium
  - Limited frequency resource in free space
  - Narrow band filtering for high density multiplexing
  - Noisy channel, fading effect, multi-path, etc….
- Optical fiber is considered as a perfectly transparent medium, but issues are there…..
  - Optical noise by EDFA
  - Fiber nonlinearity

Issues to be solved by Data Coding in Optical fiber Communication system

WDM Submarine cable system



WDM
- Spectral Overlapping
- Channel Interaction by fiber nonlinearity

Optical Repeater
- ASE Noise

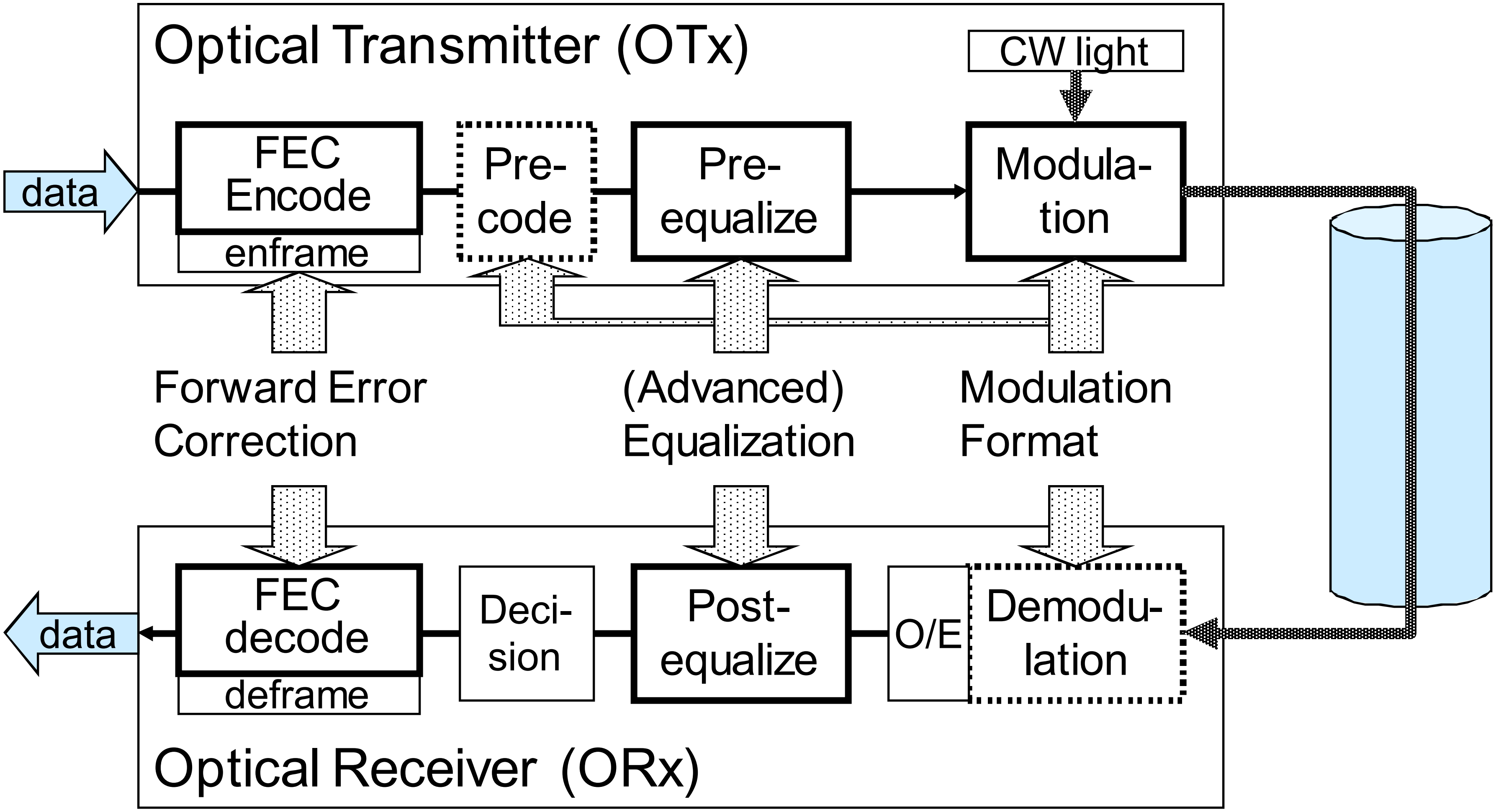
Transmission Fiber
- Chromatic Dispersion
- Fiber Nonlinearity
- Polarization Mode Dispersion

Issues to be solved by Data Coding in Optical fiber Communication system

All technologies are aiming for larger-capacity / longer system

- WDM issues
  - Spectral Overlapping: interference from neighboring channel. Random noise effect.
  - Channel Interaction by fiber nonlinearity: optical phase change due to optical intensities of neighboring channels. Induce random waveform distortion (in combination to chromatic dispersion).
- Optical Repeater issue
  - ASE Noise: optical noise generated at optical amplifiers. Random noise effect.
- Transmission Fiber issues
  - Chromatic Dispersion: propagation delay difference against signal wavelength. Induce deterministic waveform distortion.
  - Fiber Nonlinearity: optical phase change due to self optical intensity. Induce deterministic waveform distortion.
  - Polarization Mode Dispersion: propagation delay difference between two polarization modes. PMD induce deterministic waveform distortion, but PMD itself has statistical nature.

Issues to be solved by Data Coding in Optical fiber Communication system

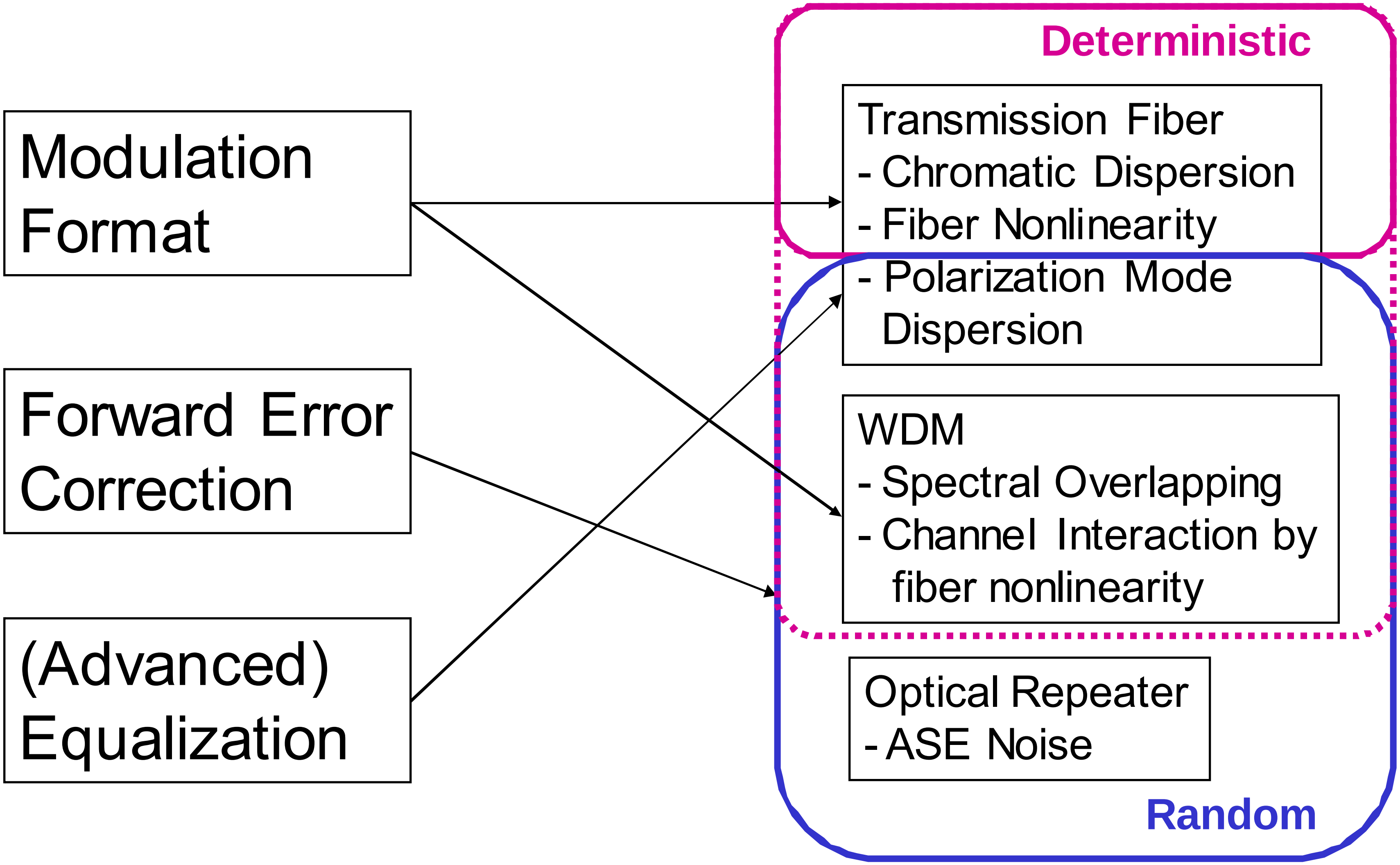


Role of three technologies in Data Coding

All technologies are for enabling larger-capacity / longer system

- **Modulation Format**
  - Assign input data to most appropriate optical state to minimize errors at the receiver which are due to various optical channel issues
- **Forward Error correction**
  - Recover errors occurred during the transmission by using redundant information added at the transmitter
- **(Advanced) Equalization**
  - Optimize the waveform of the electrical signals (modulator input at Tx / decision input at Rx) to minimize the error at decision
  - Compensate for waveform distortion due to optical channel issues at the electrical stage

Relation between data coding technologies and issues



Modulation Format

Forward Error Correction

(Advanced) Equalization

Deterministic

Transmission Fiber
- Chromatic Dispersion
- Fiber Nonlinearity
- Polarization Mode Dispersion

WDM
- Spectral Overlapping
- Channel Interaction by fiber nonlinearity

Optical Repeater
- ASE Noise

Random

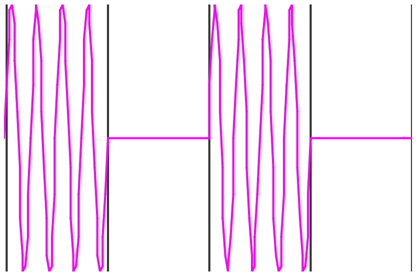
Data Coding and submarine cable system

- Transmission distance is a most critical parameter
- Transmission fiber is one of the design issue
- Limited usage of in-line devices , more flexible use at terminal

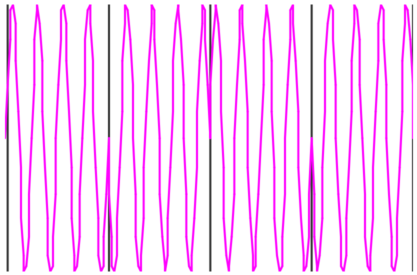
Modulation Formats

Modulation Format

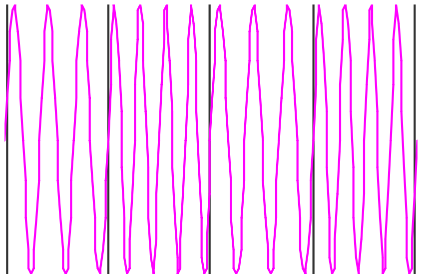
- Optical states used for modulation
  - Intensity: NRZ, RZ, chirped-RZ
  - Phase: DPSK, DQPSK, ...
  - Frequency: FSK, MSK, ….
  - Polarization states: Pol-SK
  - Combination of above: CS-RZ, duobinary, APSK, QAM, ……



Intensity



Phase



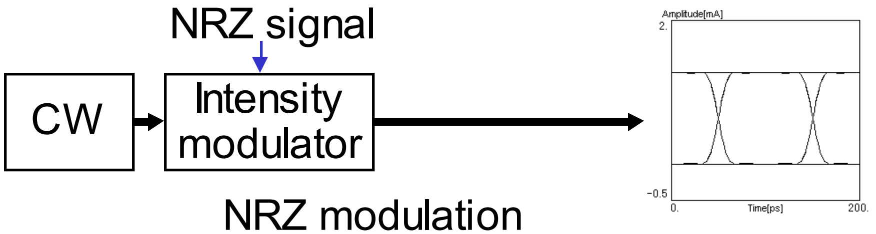
Frequency

Intensity modulation: NRZ and RZ

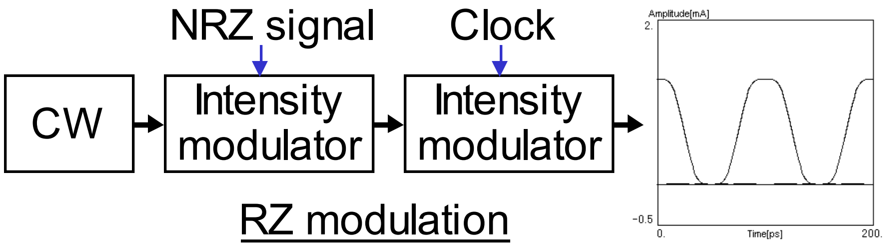
- NRZ (non return to zero)
  - Merits
    - Very simple structure
    - Moderate CD tolerance
  - Demerits
    - Large fiber nonlinearity induced distortion
    - Less tolerant to PMD.
- RZ (return to zero)
  - Merits
    - Simple structure
    - Higher optical noise tolerance
    - Moderate PMD tolerance
    - Higher nonlinearity tolerance

      Adding appropriate initial chirp (phase modulation) leads more nonlinearity tolerance (Chirped RZ)
  - Demerits
    - Smaller CD tolerance
    - Wide spectral width

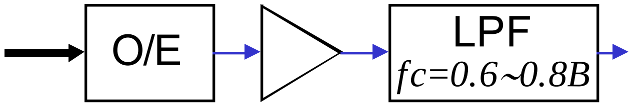
      difficult to use in dense WDM system



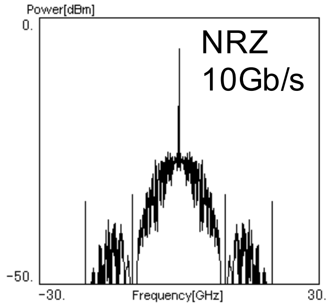
NRZ modulation

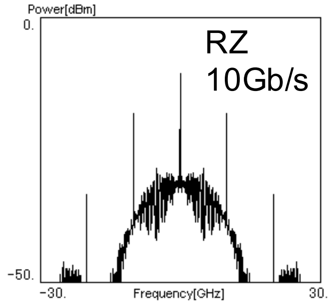


RZ modulation



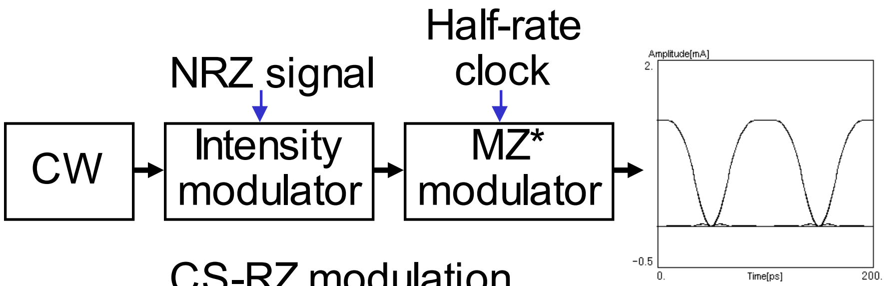
Detection/Demodulation





Carrier suppressed RZ (CS-RZ)

- Similar to RZ except that neighbor pulses have π phase shift
- Both RZ pulse carving and phase modulation can be done by single Mach-Zhender modulator
- Merits (compare to RZ)
  - – Higher fiber nonlinearity tolerance.
  - – Narrower spectral width (but wider than NRZ)
- Demerits
  - – More complex structure for pulse carving
    - half-rate clock
    - Twice the voltage swing

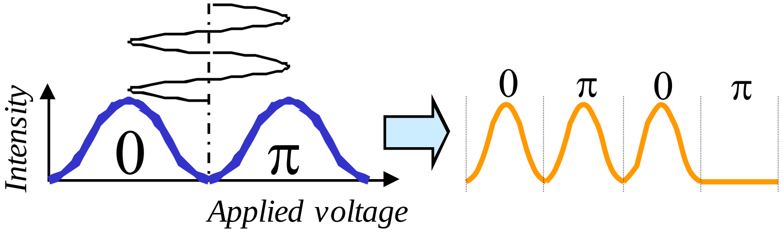

NRZ signal

Half-rate clock

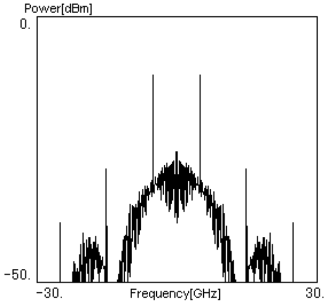
CW → Intensity modulator → MZ* modulator →

CS-RZ modulation

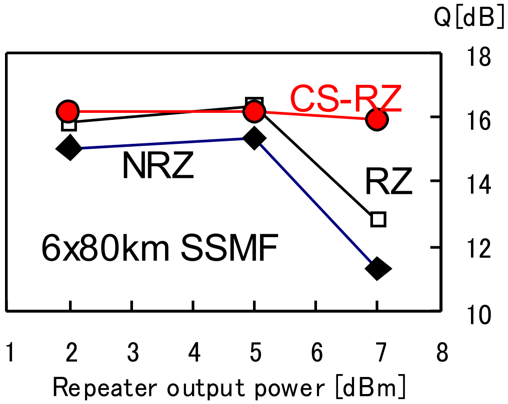
MZ: Mach-Zhender



Carrier-suppressed pulse carving



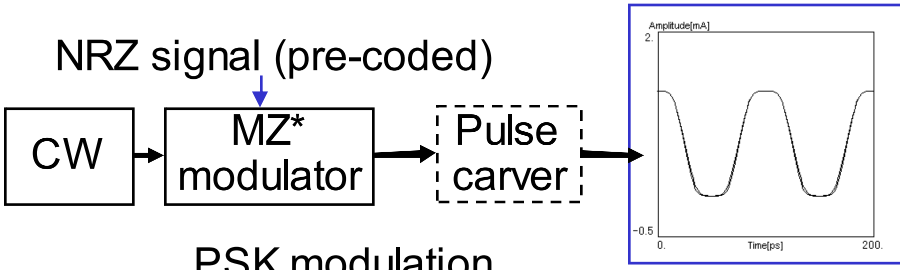
Signal spectrum



Received Q after transmission

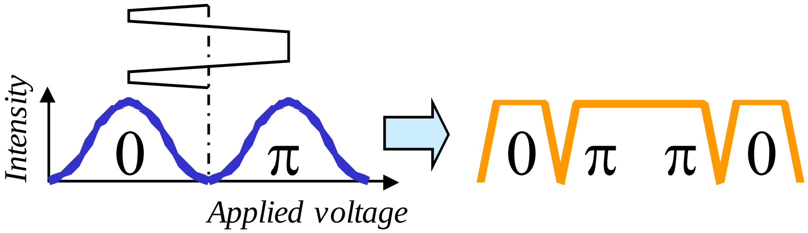
Phase modulation: Differential Phase Shift Keying (DPSK)

- PSK modulation is adopted by Mach-Zhender modulator to achieve perfect 0–π phase shift.
- Delayed interferometer is widely used at the Rx for demodulation
- Merits
  - Very high tolerance to optical noise
  - Very high nonlinearity tolerance with RZ carving.
  - Less sensitive to dispersion map
- Demerits
  - Wider spectrum width
  - Complex structure (especially at ORx)
  - Need highly coherent source

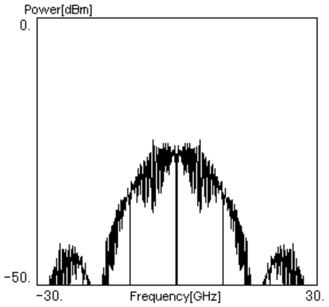


PSK modulation

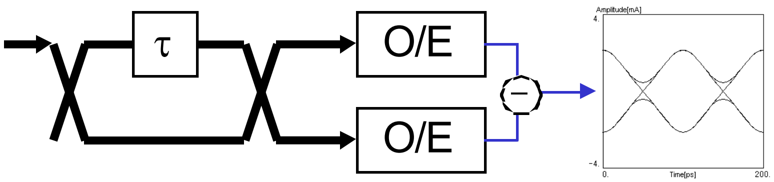
MZ: Mach-Zhender



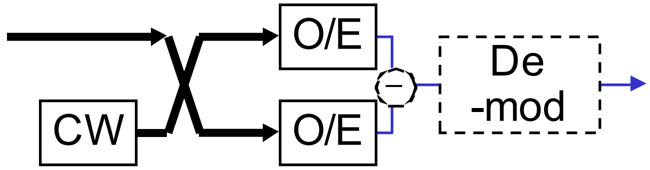
PSK modulation by MZ modulator



Signal spectrum



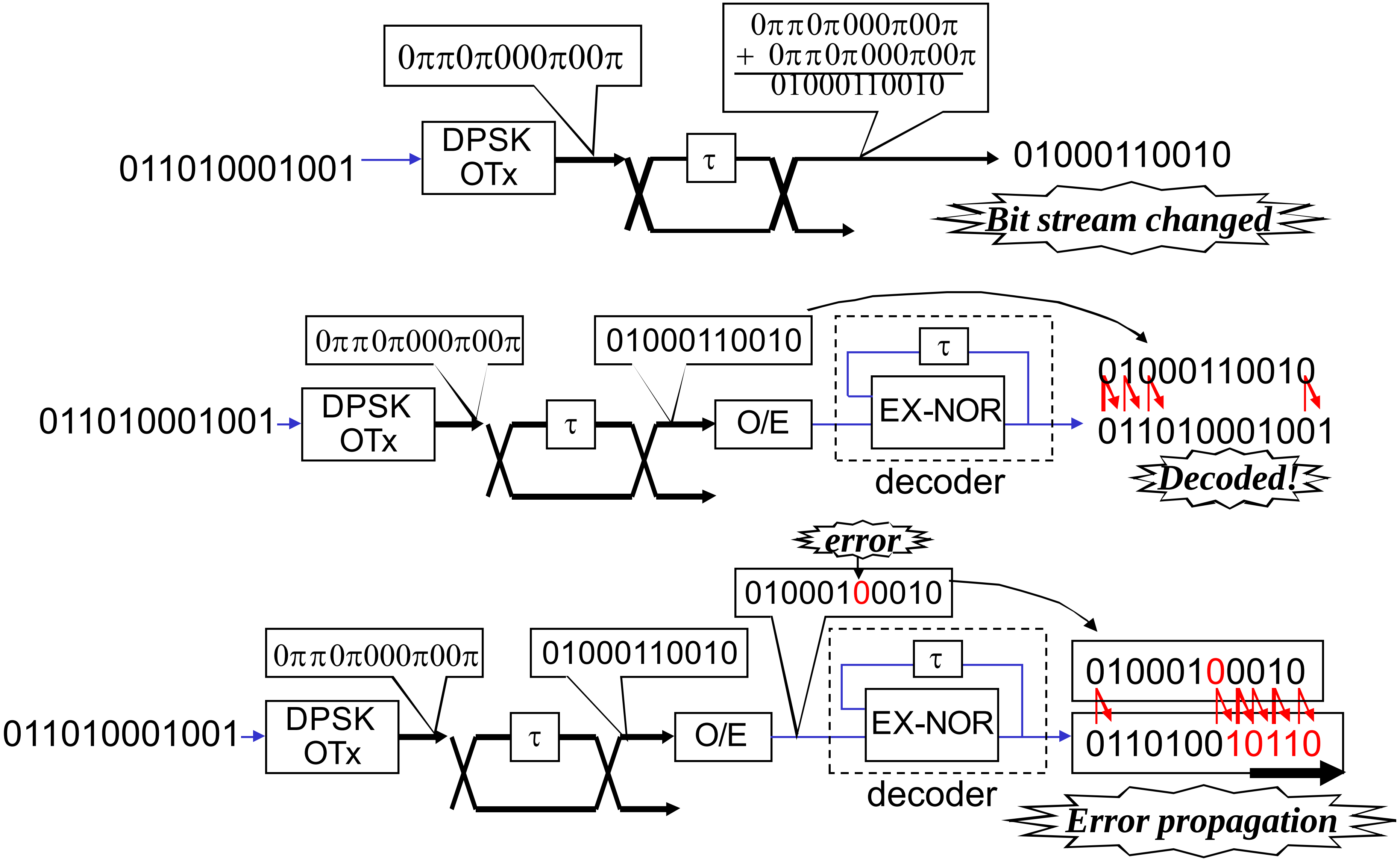
PSK to ASK by asymmetrical MZ interferometer



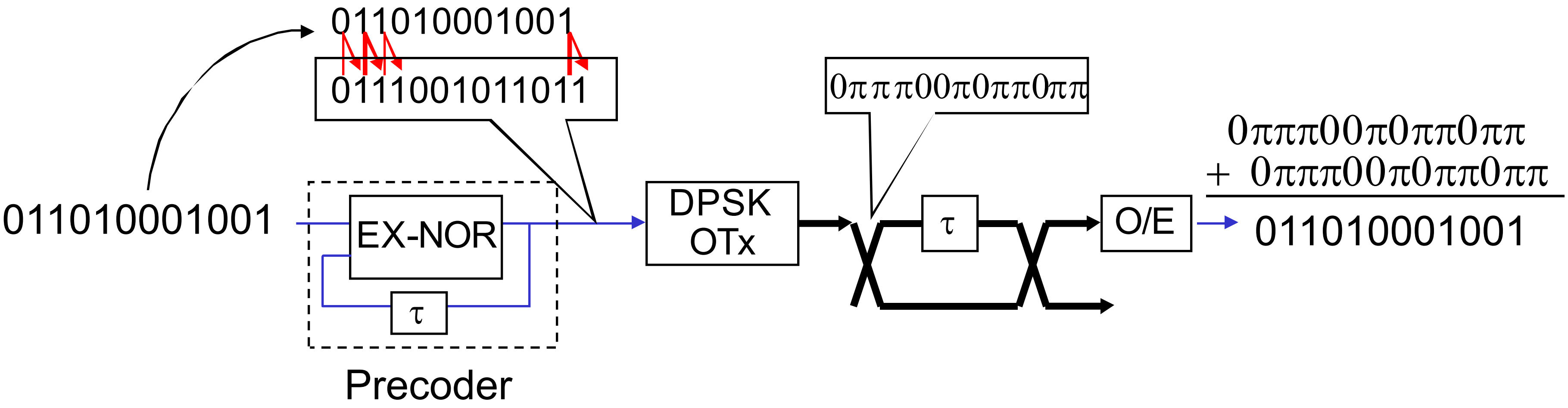
Coherent detection

Detection/Demodulation

Error propagation at decoding in delayed demodulation DPSK system



Pre-coding for delayed demodulation DPSK system



011010001001

0111001011011

011010001001

EX-NOR

τ

Precoder

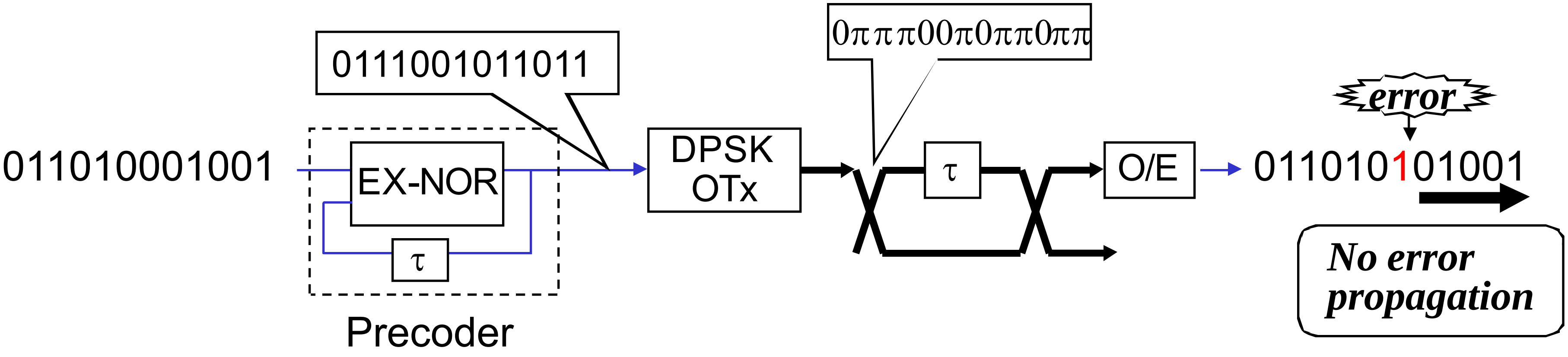
DPSK OTx

0πππ00π0ππ0ππ

τ

O/E

$$\begin{array}{r} 0\pi\pi\pi00\pi0\pi\pi0\pi\pi \\ +\ 0\pi\pi\pi00\pi0\pi\pi0\pi\pi \\ \hline 011010001001 \end{array}$$



011010001001

0111001011011

EX-NOR

τ

Precoder

DPSK OTx

0πππ00π0ππ0ππ

τ

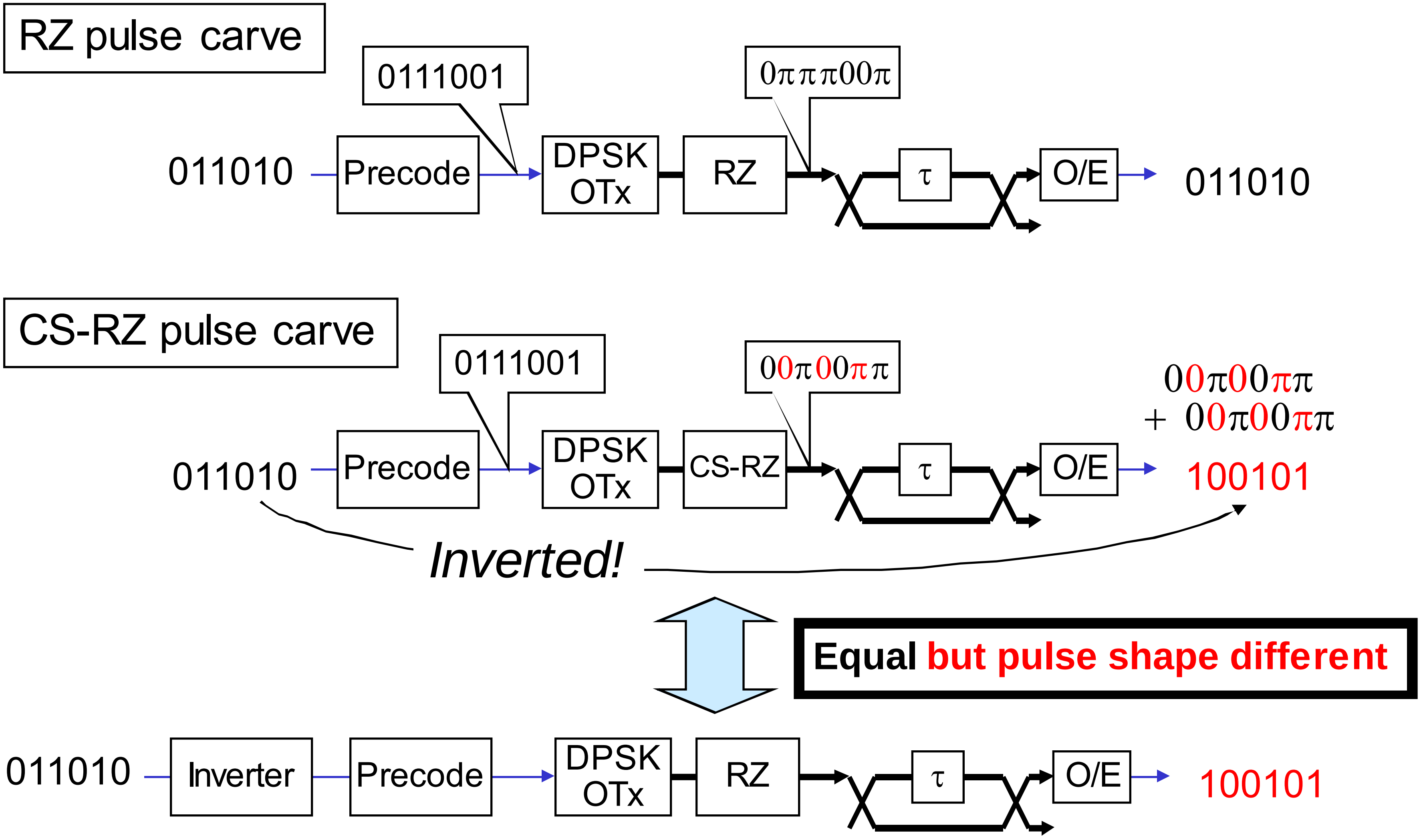
O/E

error

011010101001

No error propagation

RZ-shaper (RZ and CS-RZ) in DPSK system



RZ pulse carve

011010 → Precode → DPSK OTx → RZ → τ → O/E → 011010

0111001

0πππ00π

CS-RZ pulse carve

011010 → Precode → DPSK OTx → CS-RZ → τ → O/E → 100101

0111001

00π00ππ

00π00ππ
+ 00π00ππ

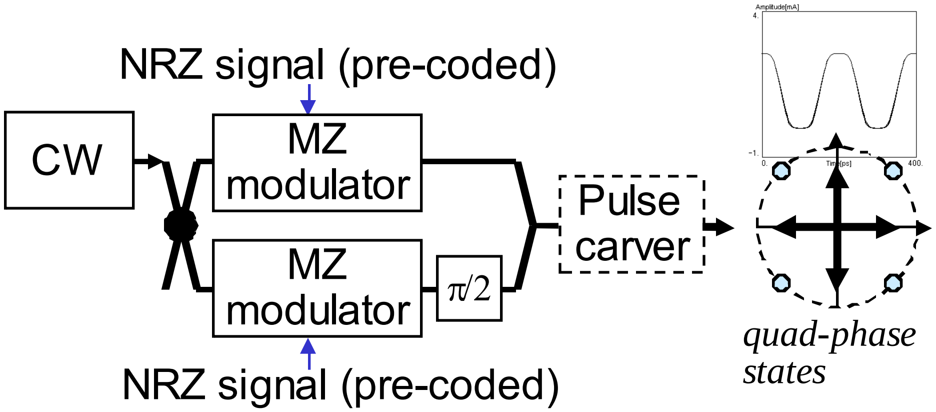
Inverted!

Equal but pulse shape different

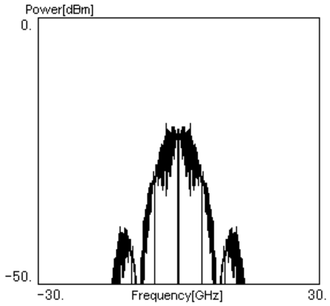
011010 → Inverter → Precode → DPSK OTx → RZ → τ → O/E → 100101

Differential Quadrature Phase Shift Keying (DQPSK)

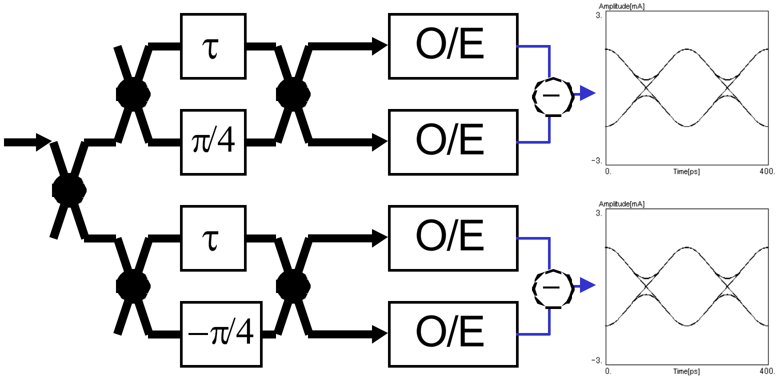
- Parallel MZ modulator is used to generate precise quadrature-phase state.
- Two sets of delayed interferometer are used to demodulate I and Q channels.
- Merits
  - Narrower spectral width
  - High CD tolerance
  - High PMD tolerance
  - Theoretically, comparable optical noise tolerance to DPSK
- Demerits
  - Very complex structure
  - Very sensitive to source frequency drift.
  - Need very narrow linewidth source



DQPSK modulation



Signal spectrum



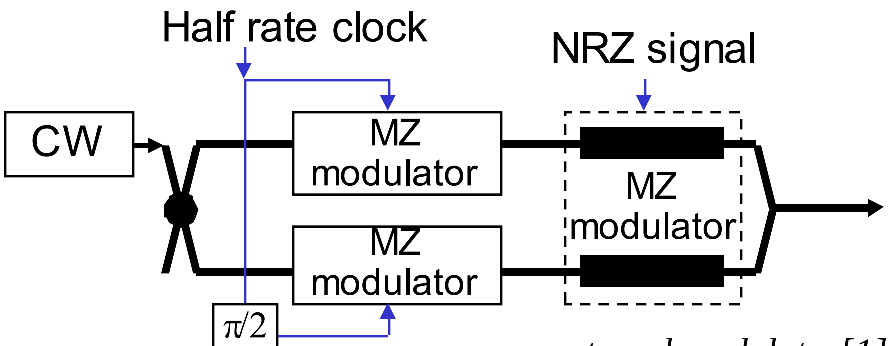
PSK to ASK by asymmetrical MZ interferometer

Detection/Demodulation

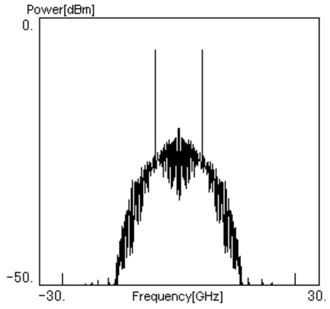
Frequency modulation: Frequency Shift Keying (FSK)

- Merits
  - Very high tolerance to optical noise (Comparable to PSK formats)
  - Compact Spectrum Profile
- Demerits
  - High speed modulation difficult for direct modulation
  - Complex structure (especially at ORx)
  - Need highly coherent source
- For High speed application, CPFSK modulations using external modulator proposed[1,2]

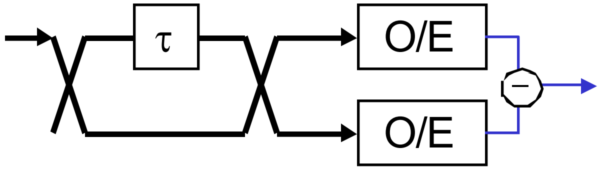
direct modulation



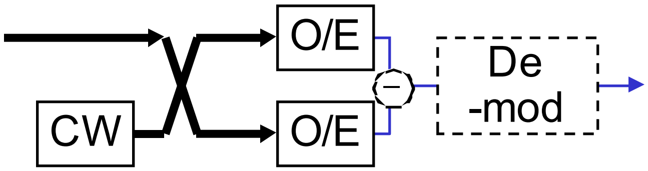
external modulator[1]



Signal spectrum



FSK to ASK by asymmetrical MZ interferometer

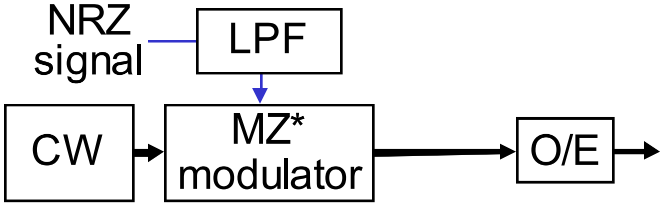


Coherent detection

Detection/Demodulation

More Advanced Format (terrestrial application and R&D)

Optical duobinary



NRZ signal

LPF

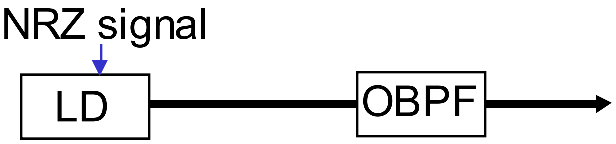
CW

MZ* modulator

O/E

- Merits
  - Simple, narrower spectral width
- Demerits
  - Lower receiver sensitivity

Chirp managed Laser[3]



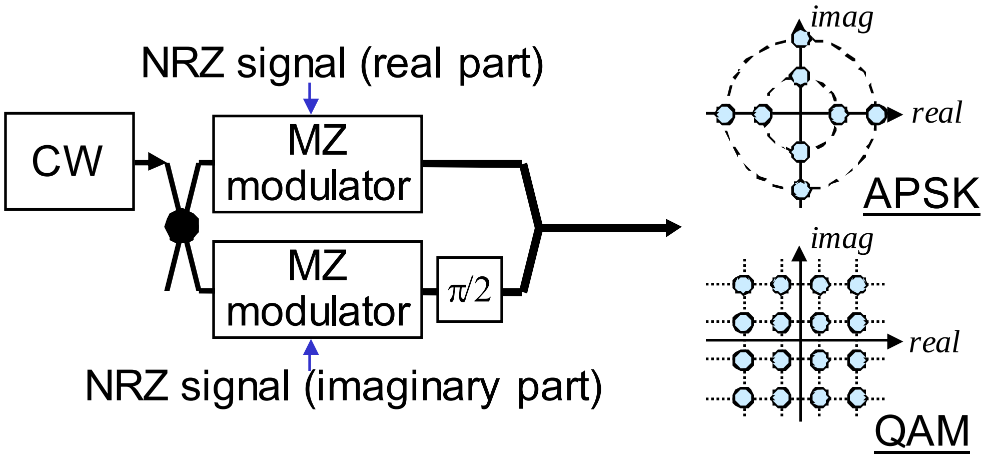
NRZ signal

LD

OBPF

- Merits
  - Simple, large CD tolerance
- Demerits
  - Limited by the FM bandwidth of the LD

Amplitude-Phase shift Keying[4], QAM[5]



NRZ signal (real part)

CW

MZ modulator

MZ modulator

$\pi/2$

NRZ signal (imaginary part)

- Merits
  - Narrow spectrum width
  - Large CD / PMD tolerance
- Demerits
  - Complex structure
  - Highly coherent source with stabilized frequency is required.

Merits and demerits

Format	Noise tolerance	Nonlinearity tolerance	Spectrum width	CD tolerance	PMD tolerance	complexity
NRZ	Fair	Fair	Fair	Fair	Fair	Excellent
RZ	Good	Good	Poor	Poor	Good	Good
Chirped RZ	Good	Excellent	Poor	Poor	Good	Good
CS-RZ	Good	Excellent	Fair--	Fair--	Good	Fair++
DPSK	Excellent	Good+	Fair--	Fair--	Good	Fair
DQPSK	Good+	Good	Good	Excellent	Excellent	Fair--
FSK	Good+	?	Good	Good?	?	Fair--
Duobinary	Poor	Fair--	Excellent	Excellent	Fair--	Good
CML	Fair	?	Fair++	Excellent	Fair	Fair++
APSK	Fair--	?	Excellent	Excellent	Good+?	Poor
QAM	Fair--	?	Excellent	Excellent	Good+?	Poor

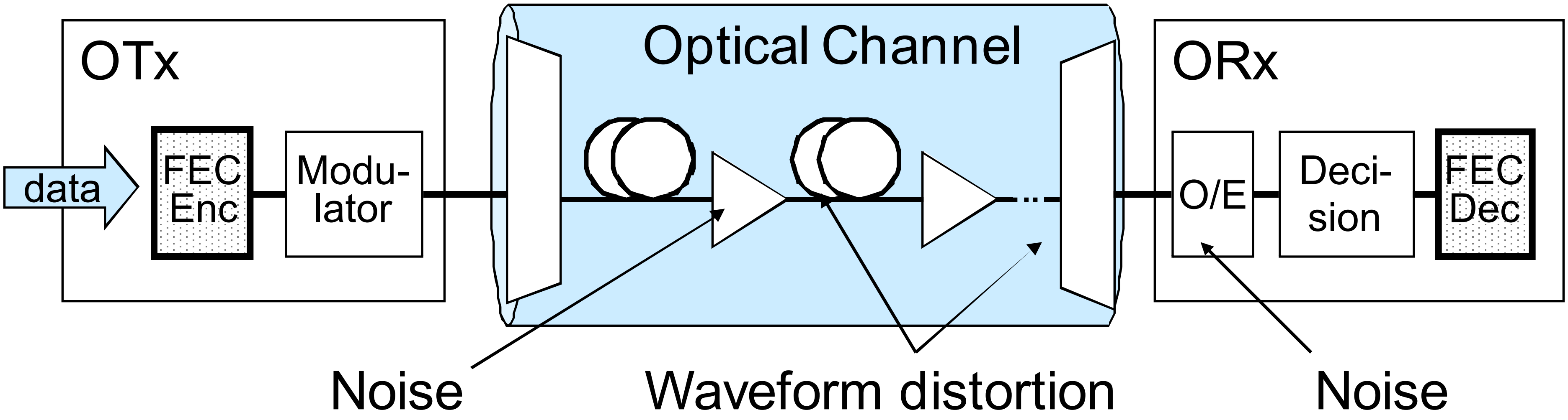
Recent results in long-haul transmission experiment

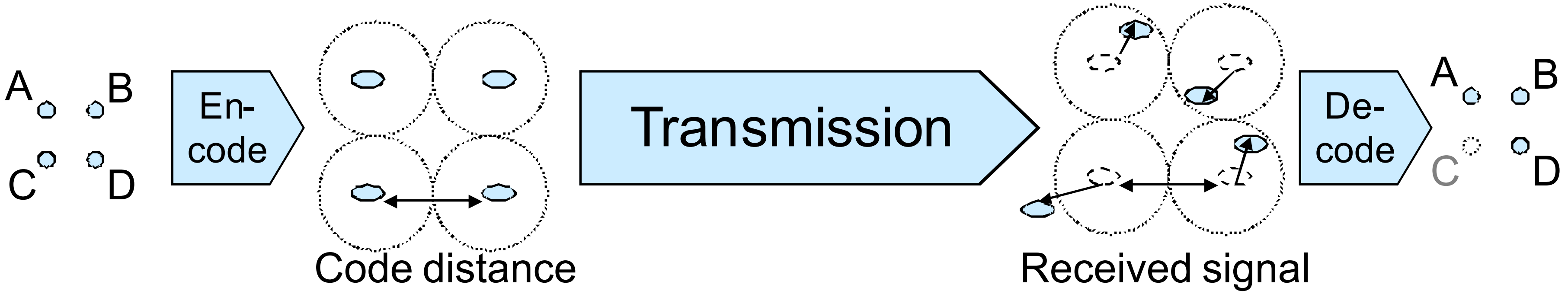
Conference	Paper No.	Affiliation	Ch x bitrate	distance	Modulation format and other features
ECOC ’04	Th3.5.4	NEC	50x42.8Gb/s	6,000km	CS-RZ
ECOC ’04	Th4.1.3	KDDI	32 x 12.4Gb/s	9,000km	CS-RZ DPSK
OFC ’05	PDP28	Univ. Eindhoven	22 x 20Gb/s	10,200km	RZ-DQPSK, optical phase conjugation
OFC ’05	PDP27	Nortel	10Gb/s	5,100km	DPSK, electricl pre-equalization
OFC ’05	PDP26	Tyco	18x40Gb/s	6,250km	RZ-DPSK
ECOC ‘05	Mo.3.2.2	Alcatel	64x12.3Gb/s	12,700km	RZ-DPSK
ECOC ‘05	Th.4.1.3	Alcatel	151 x 43Gb/s	4,080km	RZ-DQPSK
ECOC ‘05	Th.4.1.5	Univ. Eindhoven	26 x 42.8Gb/s	4,500km	RZ-DQPSK, optical phase conjugation
ECOC ‘05	Th.4.2.5	Lucent	10Gb/s	9,280km	CML (RZ-AMI)
OFC ‘06	PDP33	Tyco	28 x 43Gb/s	6,550km	Chirped RZ - DQPSK
ECOC ‘06	Th.4.1.7	Tyco	93 x 10Gb/s	8,900km	RZ-DPSK, 150km span
ECOC ‘06	Th.4.1.3	Lucent	10 x 107Gb/s	2,000km	RZ-DQPSK
ECOC ‘06	Mo.3.2.3	Univ. Eindhoven	42.8Gb/s	3,970km	RZ-DQPSK, optical phase conjugation

Forward Error Correction for optical system

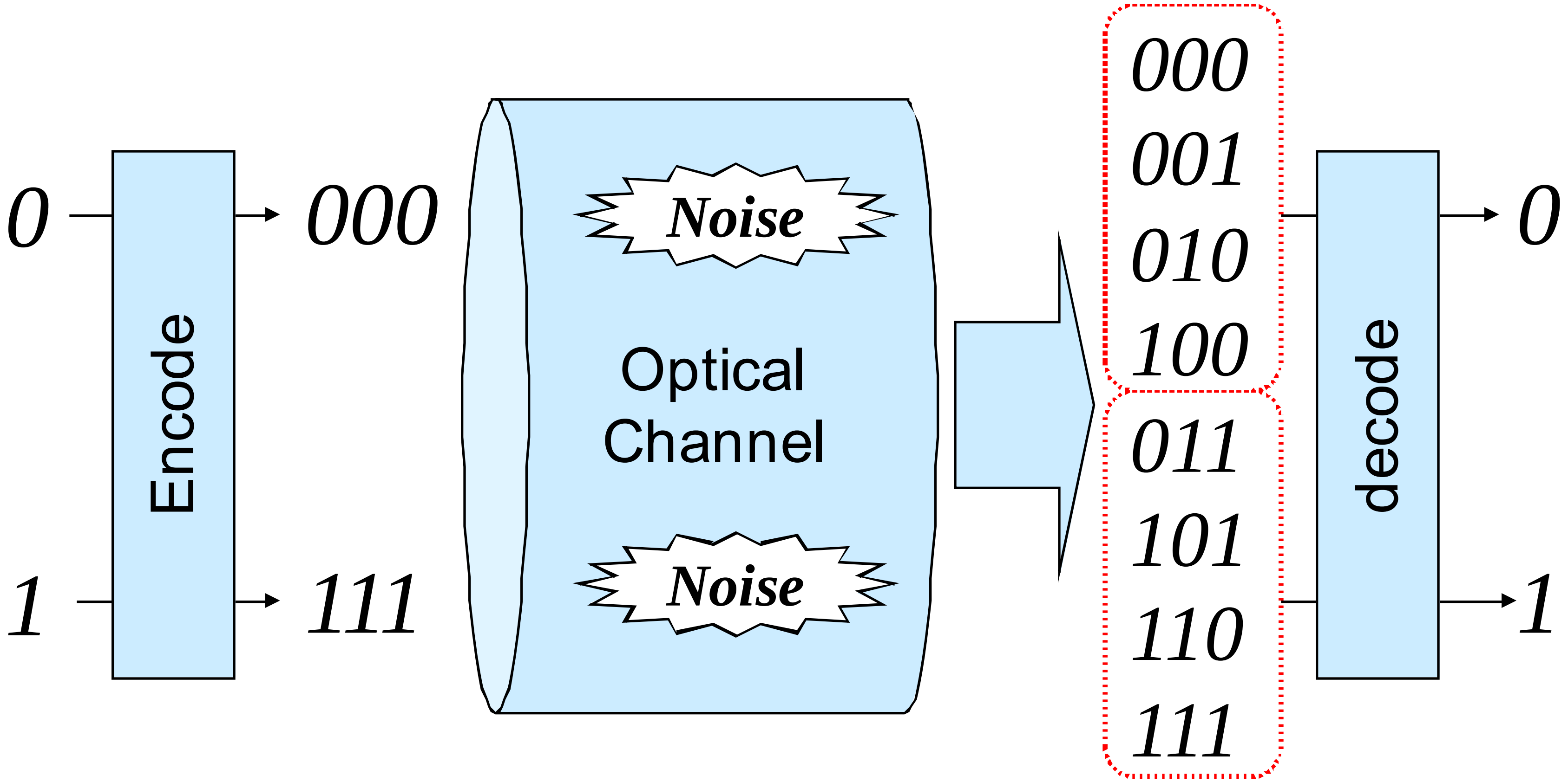
Forward Error Correction for optical transmission system

Extend the code-distance by adding redundant information on the data stream to correct errors at the receiver





Principle of FEC (very simple example)



1bit correction

Various Forward Error Correction Technologies

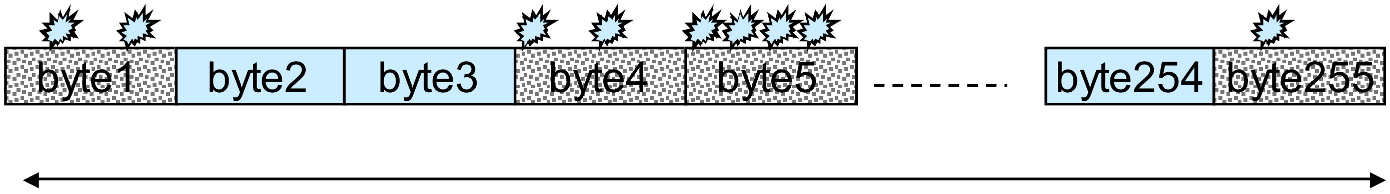
- Hamming codes

- Reed-Solomon codes
  - ITU-T standard: RS(239, 255)
- BCH (Bose, Chaudhuri, Hocquenghem) codes

- Concatenated codes
  - Turbo codes (Block turbo codes): high performance
- LDPC (Lightweight density parity check) codes
  - High performance

Reed Solomon codes (1)

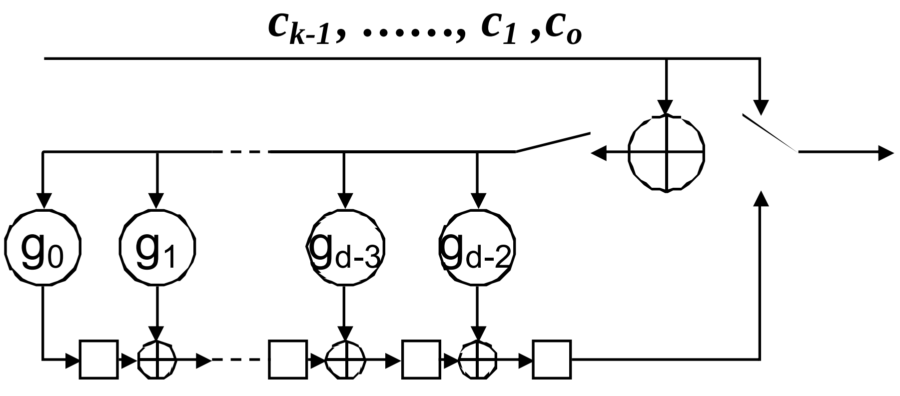
- Symbol error correction (↔ bit error correction)
  - Not perfectly fit to optical system with random noise.
- Belongs to the family of systematic linear cyclic block codes
  - easy to implement in high speed operation using shift register structure
- ITU-T G.709 Standardized: RS(239, 255)
  - 239-byte information, 16-byte redundancy
  - Correction of upto 8 bytes are possible



byte1 byte2 byte3 byte4 byte5 -------- byte254 byte255

Correct up to 8 bytes by RS(255,239)

Reed Solomon codes (2)



encoder

Calculate syndrome

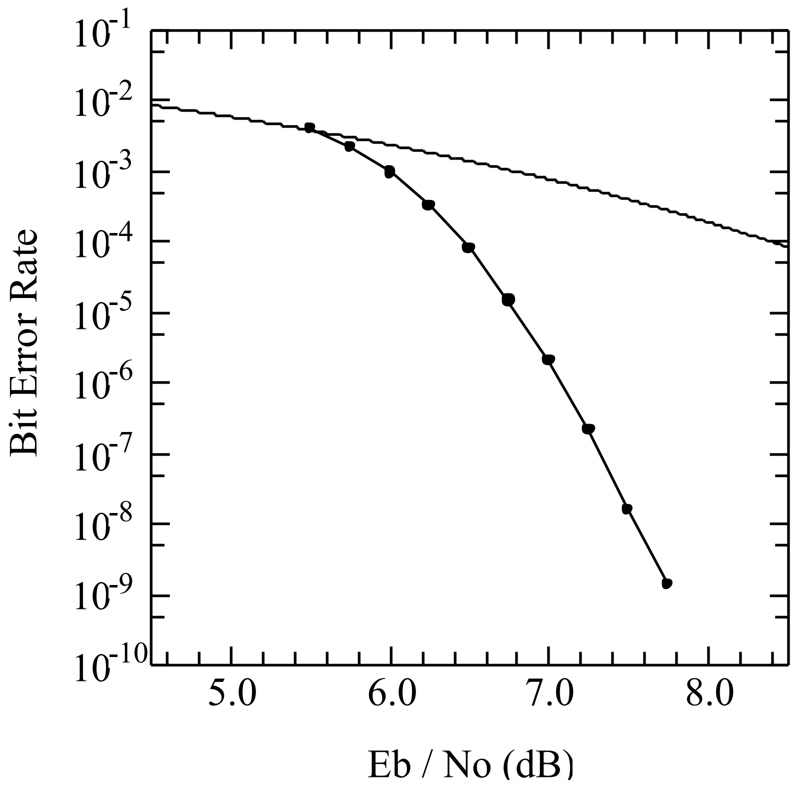
Calculate number of errors

Calculate error positions

Correct errors

decoder

RS(239,255)

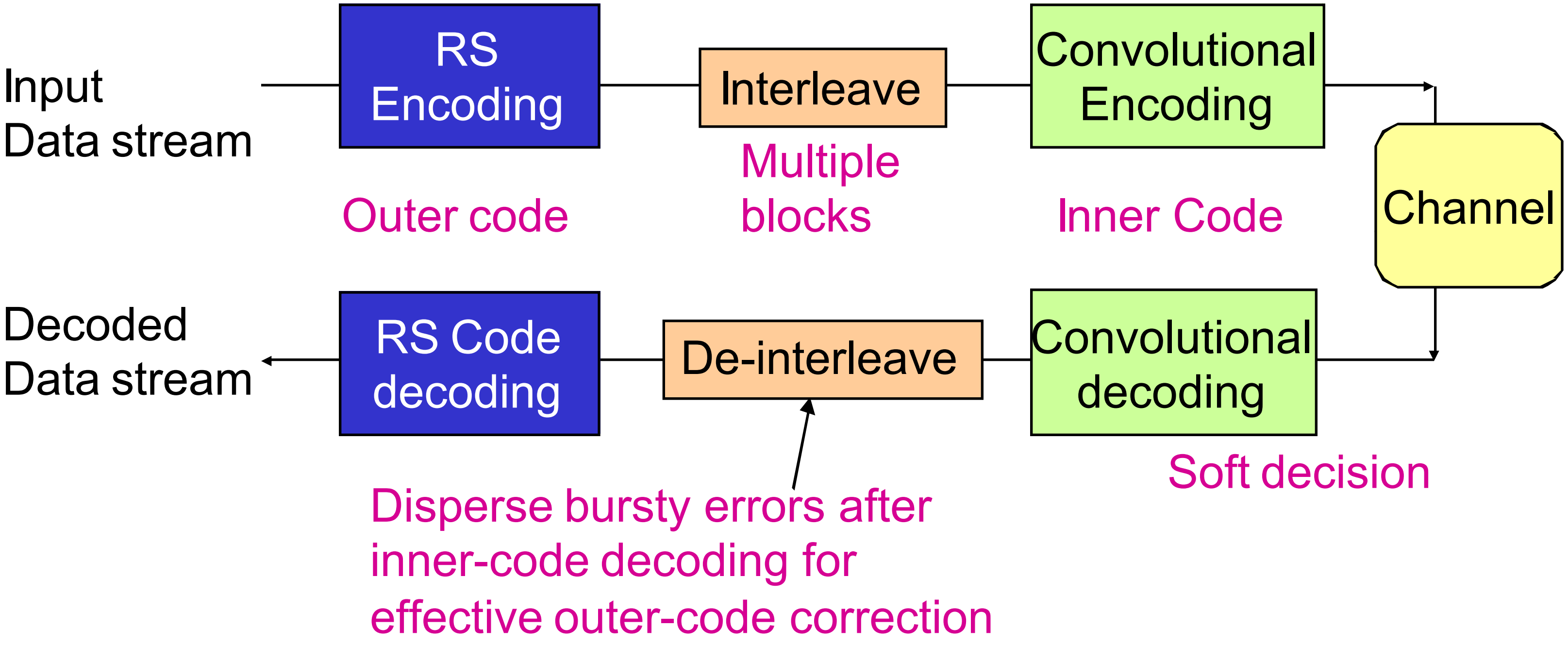


Error correction performance

Concatenated codes

Achieve high performance FEC code by combining two FEC codes, without increasing complexity in decoding

Example - Convolutional code and Reed-Solomon code
- Turbo Code



Input Data stream

RS Encoding

Interleave

Convolutional Encoding

Channel

Outer code

Multiple blocks

Inner Code

Decoded Data stream

RS Code decoding

De-interleave

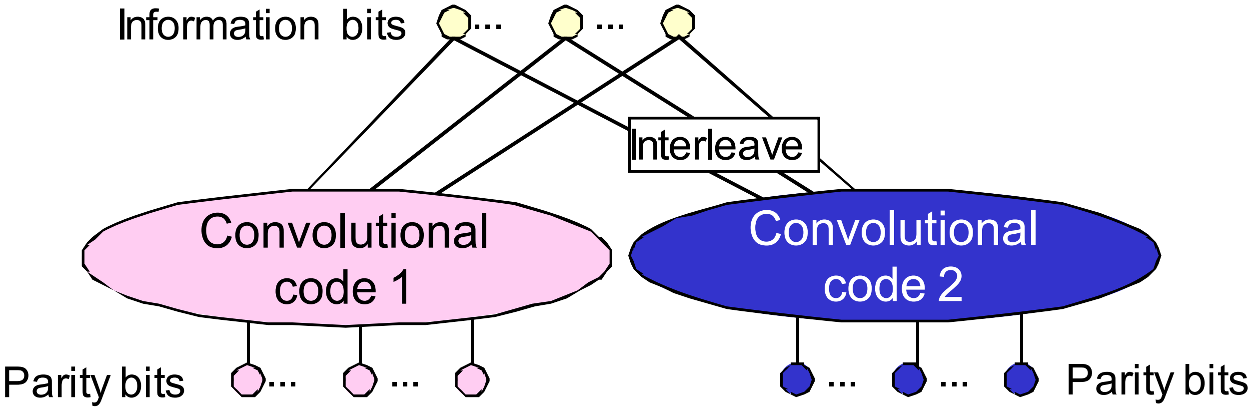
Convolutional decoding

Soft decision

Disperse bursty errors after inner-code decoding for effective outer-code correction

Iterative decoding in Turbo code

Turbo Code structure (Tanner graph expression)

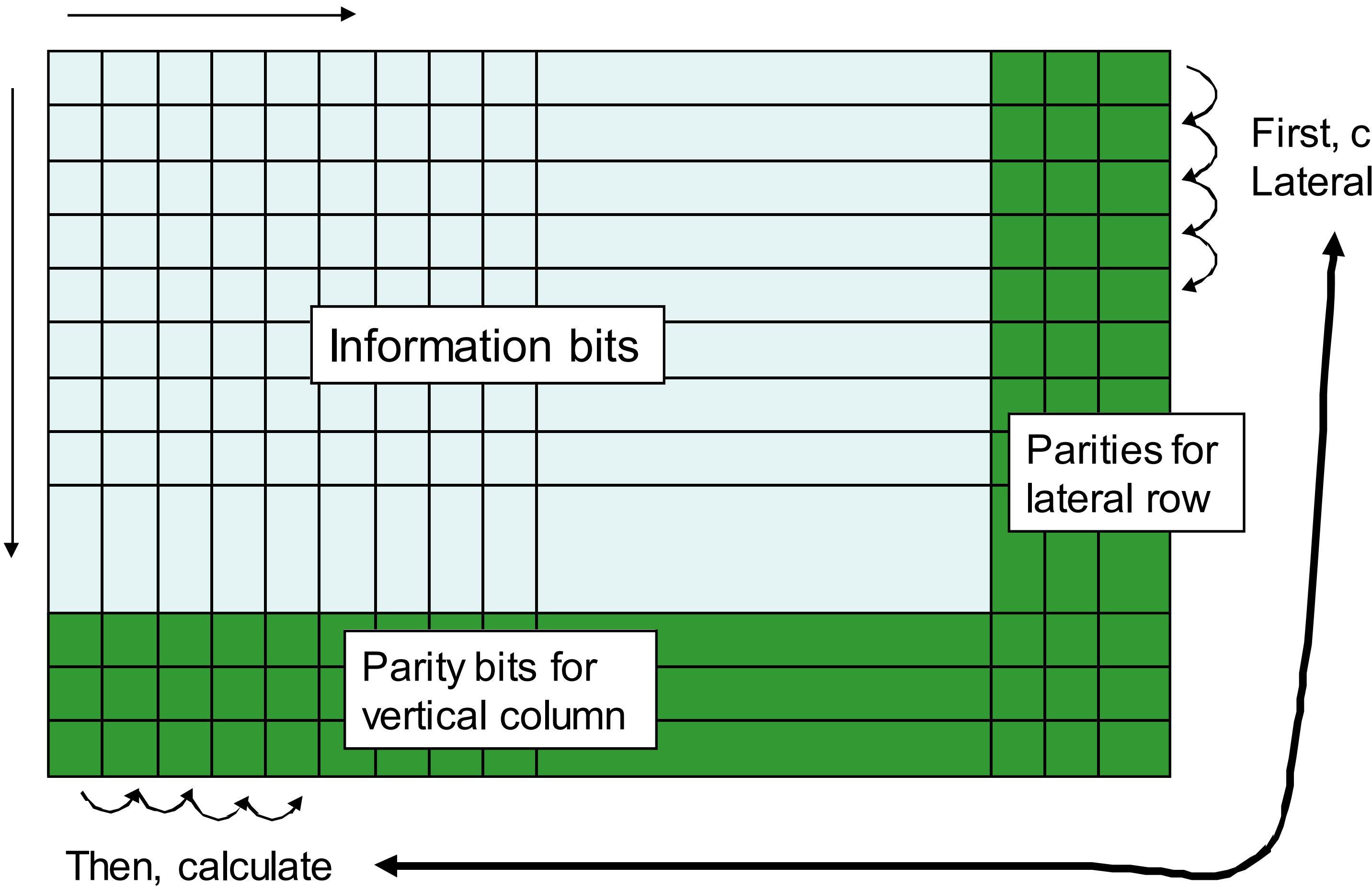


1. Soft decoding of convolutional code 1
2. Using result of step 1, generate input data to convolutional code 2 process, including interleaving.
3. Soft decoding of convolutional code 2
4. Using result of step 3, generate input data to convolutional code 1 process
5. Repeat step 1 to step 4 (4 to 30 times)

Turbo Product Code

lateral: (n_1, k_1)block code (minimum distance: d_1)

Vertical (n_2, k_2) Block code (minimum distance: d_2)



Information bits

Parities for lateral row

Parity bits for vertical column

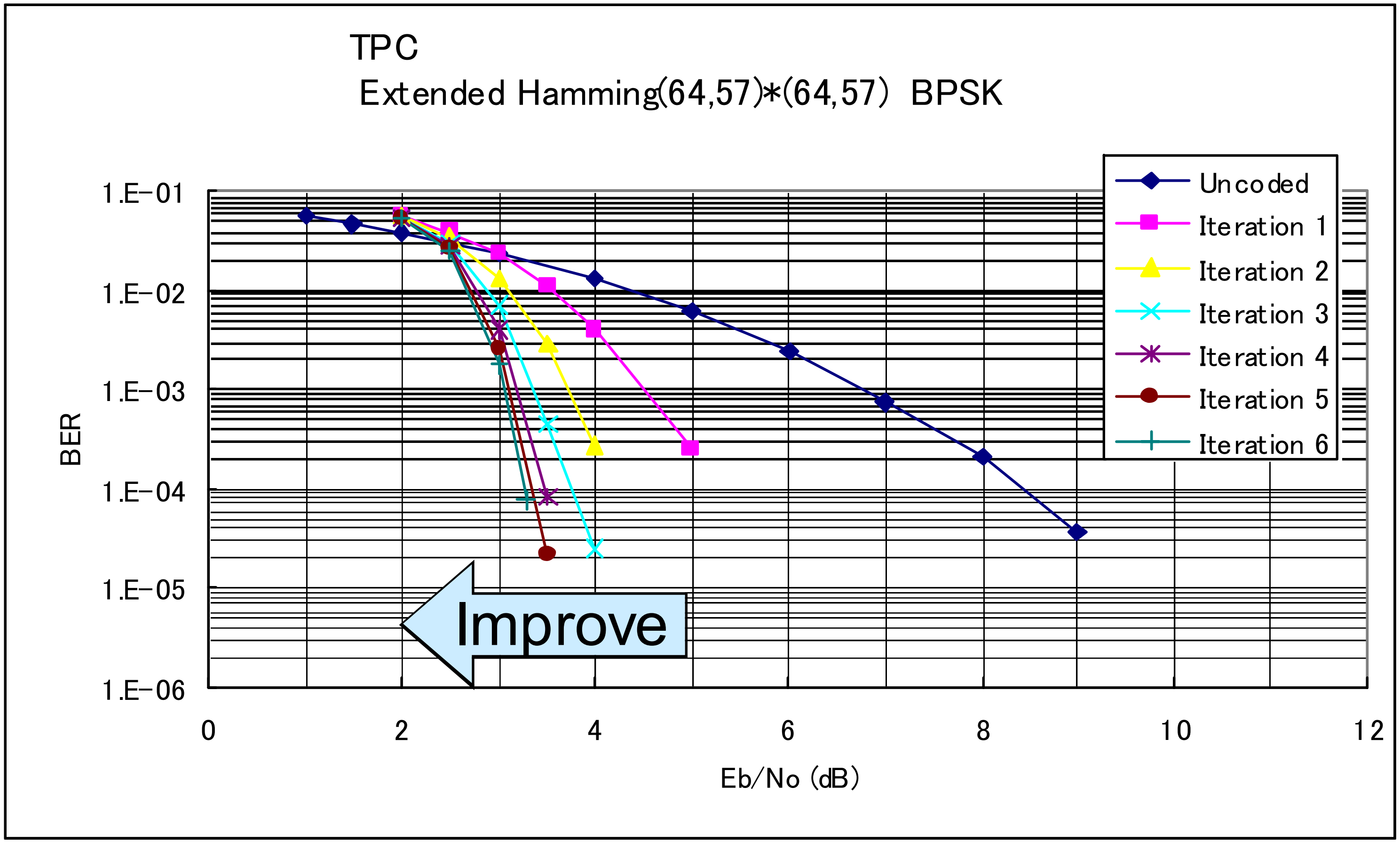
First, calculate Lateral row

Then, calculate Vertical column

Repeat

最小距離 ＝ $d_1 d_2$

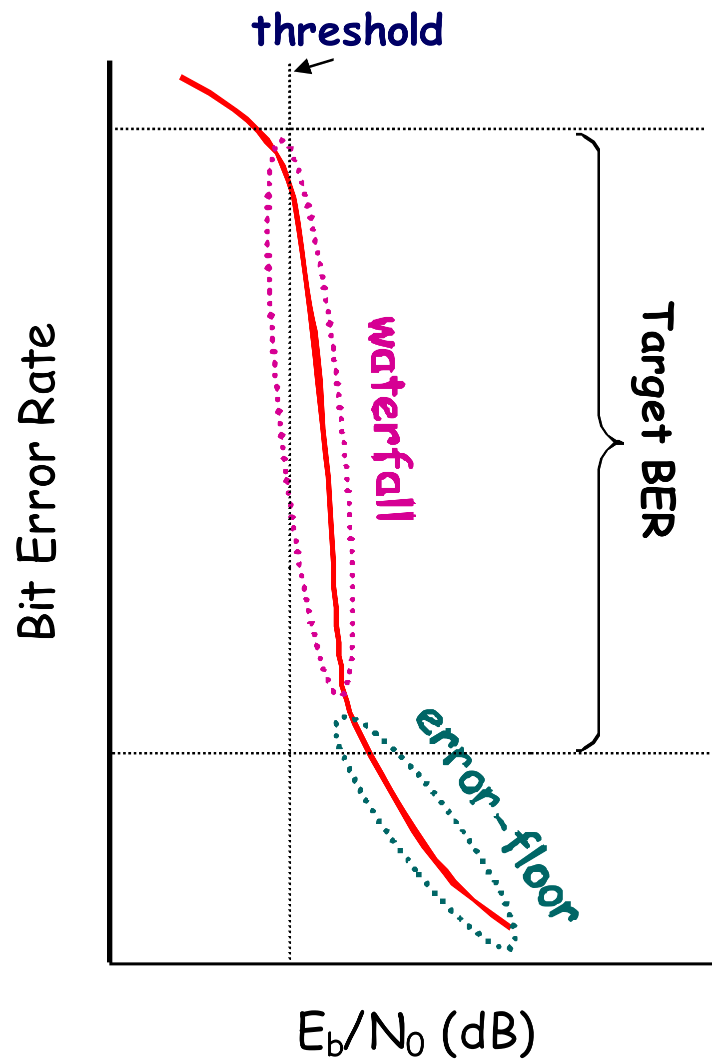
Iterative decoding result of Turbo Product code



Low Density Parity Check (LDPC) codes

- Proposed by Gallager in 1962
- Small numbers of non-zero element in parity check matrix
- Excellent correction ability
  - Close to Shannon limit performance
- Relatively easy to decode sub-optimally using iterative decoding algorithms
- Easy to implement parallel processing
  - High speed implementation possible

Features on LDPC codes



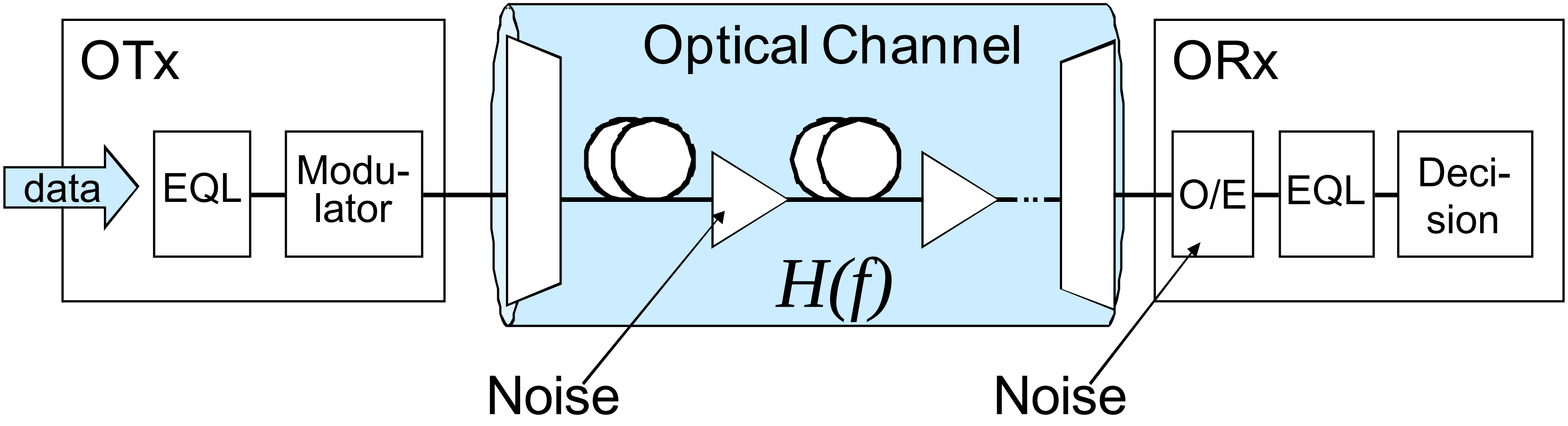
- codes having sparse parity-check matrices
  - wide class of linear block codes
  - poor distance spectra
- suboptimal decoding algorithm with feasible computational complexity
  - soft-decision decoding
  - trade-off between throughput and hardware complexity
- error performance
  - waterfall region ~ Shannon limit (for long, well-designed codes)
  - error floor

Recent results in high performance FEC for optical fiber communication system

Conference	Paper No.	Affiliation	FEC
OFC '05	OThW3	Univ. Kiel	Irregular LDPC, 10.2dB net coding gain
OFC '05	OThW4	Chalmars Univ.	Convolutional code for DPSK system
OFC '05	OThW6	Univ. Arizona	LDPC and turbo code study
OFC '05	OFO1	Mitsubishi	Invited talk of block turbo code
ECOC '05	Tu3.2.4	Univ. Kiel	Serial concatenated code, 8.6dB coding gain
ECOC '05	Tu.3.2.5	Univ. College Cork	Study of concatenated Reed-Solomon codes
ECOC '05	Tu.1.2.4	Univ. Arizona	combined constrained-iterative FEC scheme for high-speed long-haul transmission
OFC '06	OTuK4	Mitsubishi	10Gb/s block turbo code, 10.1dB coding gain
OFC '06	OThD2	Univ. Arizona	Invited talk of LDPC codes for optical communication
ECOC '06	We.1.5.6	Mitsubishi	10Gb/s block turbo code LSI with 3-bit soft decision
ECOC '06	WE.3.p.101	Univ. Kaiserslautern	Study of iterative equalization and MLSE considering outer FEC code

Advanced Equalization

Equalization in Optical Communication



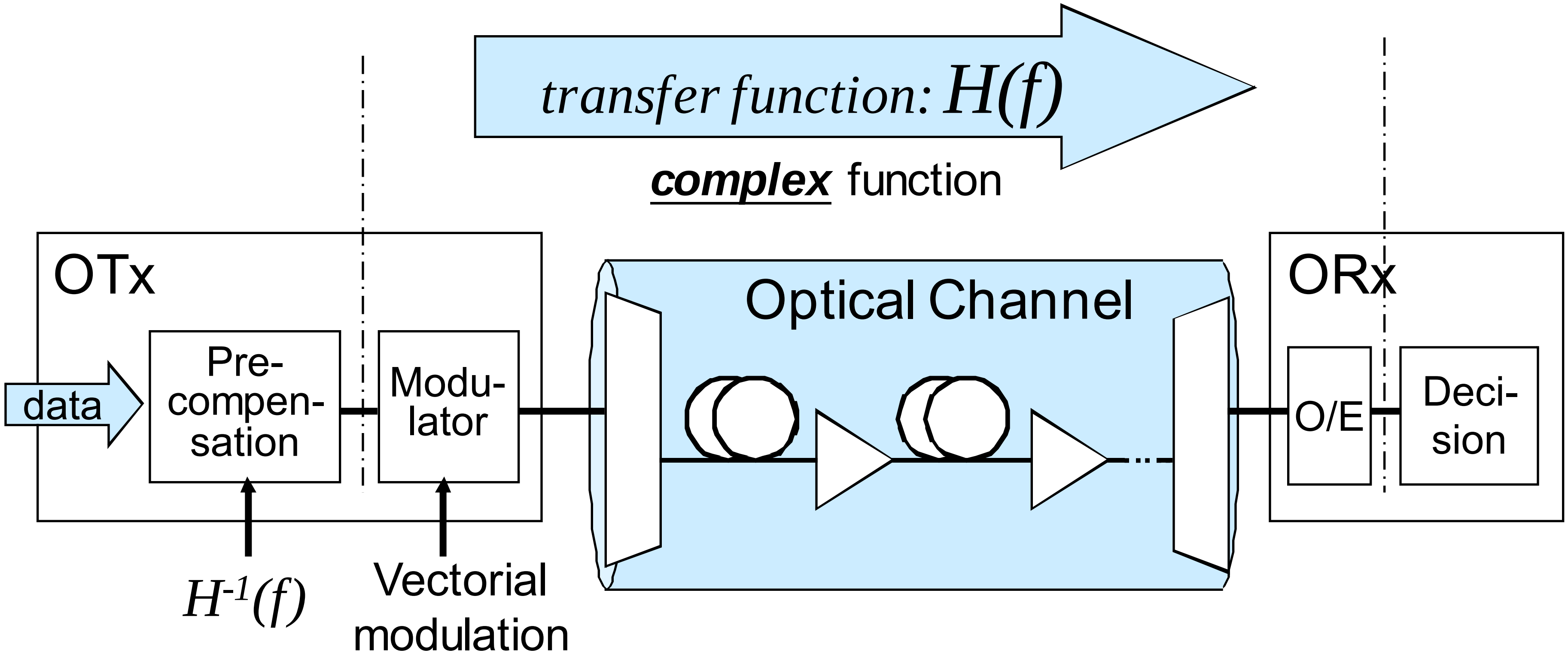
Phase 1
Minimize thermal and shot noise at receiver

Phase 2
Maximize eye opening for high speed

Phase 3
Compensate / equalize transmission Line impairment

Early stage → EDFA Era → Dynamic EQL

Pre compensation technique



transfer function: $H(f)$

complex function

OTx

data

Pre-compensation

Modulator

$H^{-1}(f)$

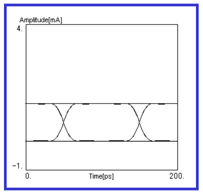
Vectorial modulation

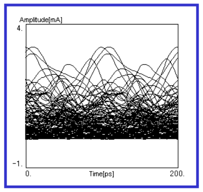
Optical Channel

ORx

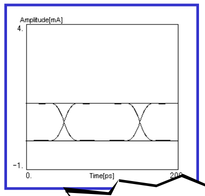
O/E

Decision



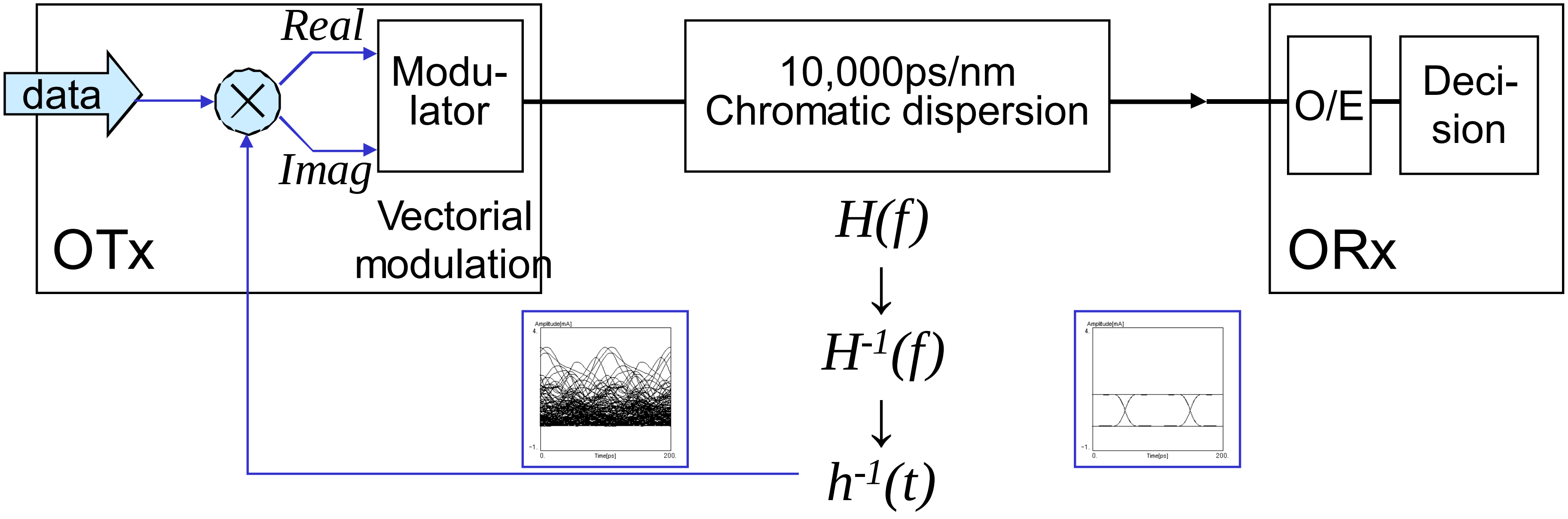


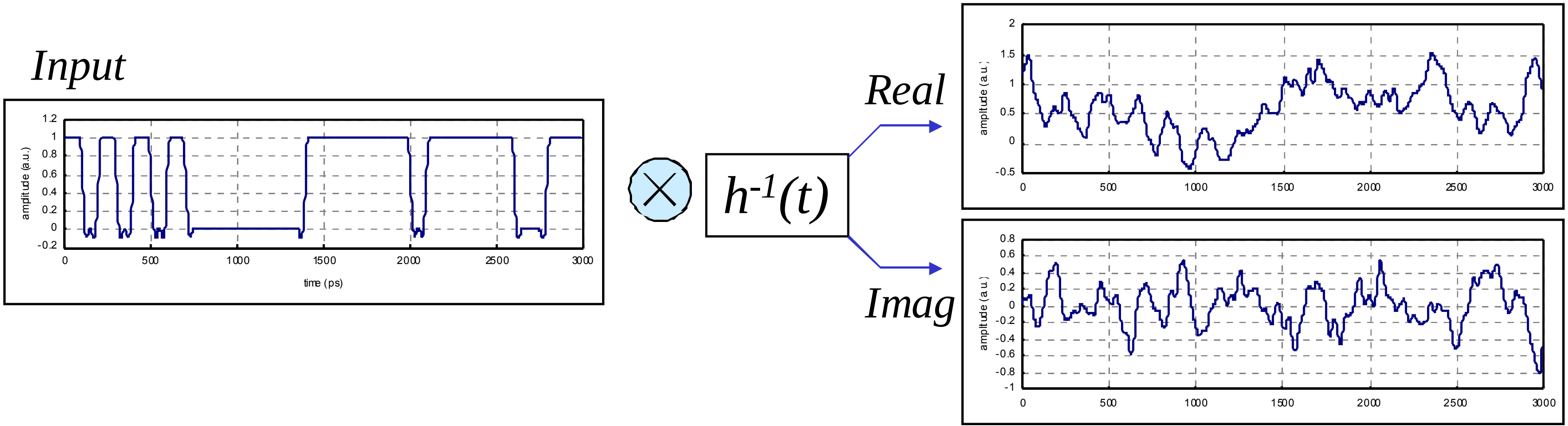
$H^{-1}(f)*H(f)$



recovered

Example of Pre-compensation

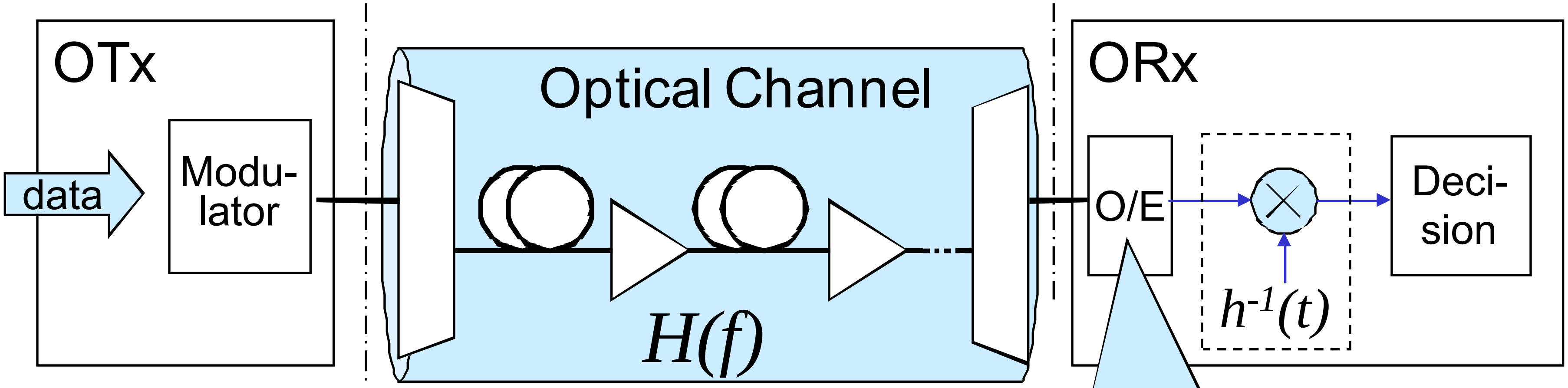




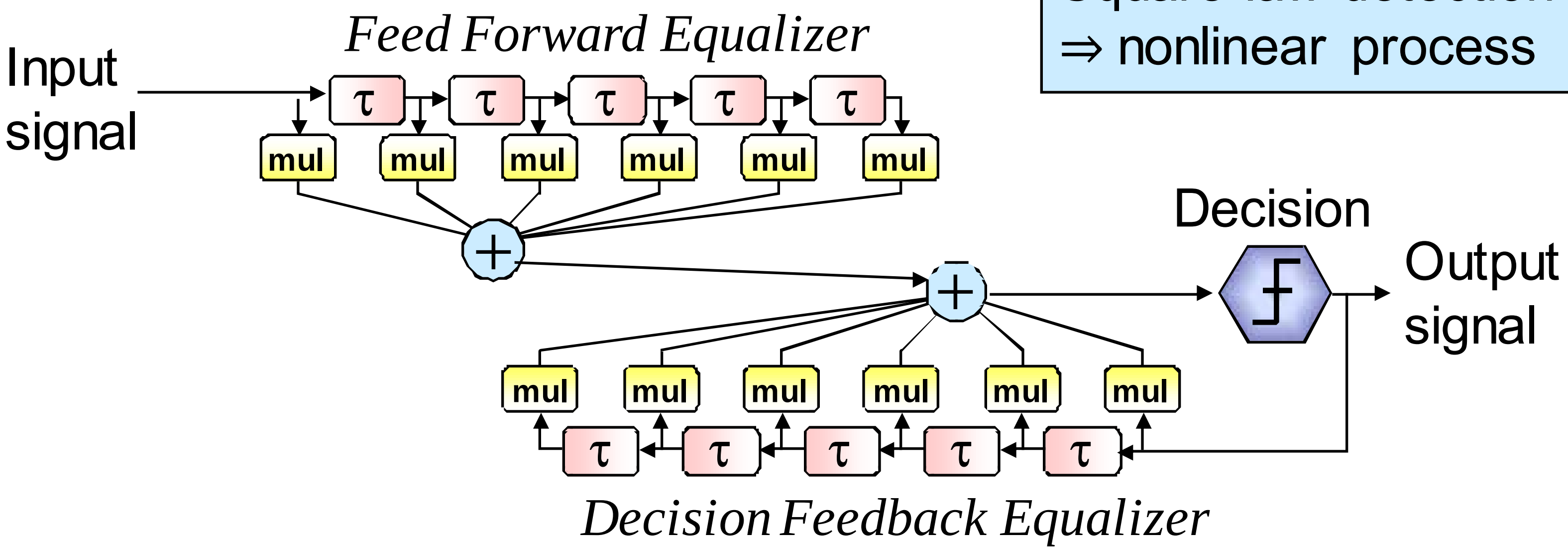
Merits and Demerits of pre-compensation

- Merit
  - Arbitrary equalization of linear optical channel effect is possible
  - Electrical implementation applicable
- Demerits
  - Fast adaptation difficult (need feedback to OTx)
  - Need large-scale, complex signal processing

Receiver-side equalization
Feed Forward Equalizer, Decision Feedback Equalizer

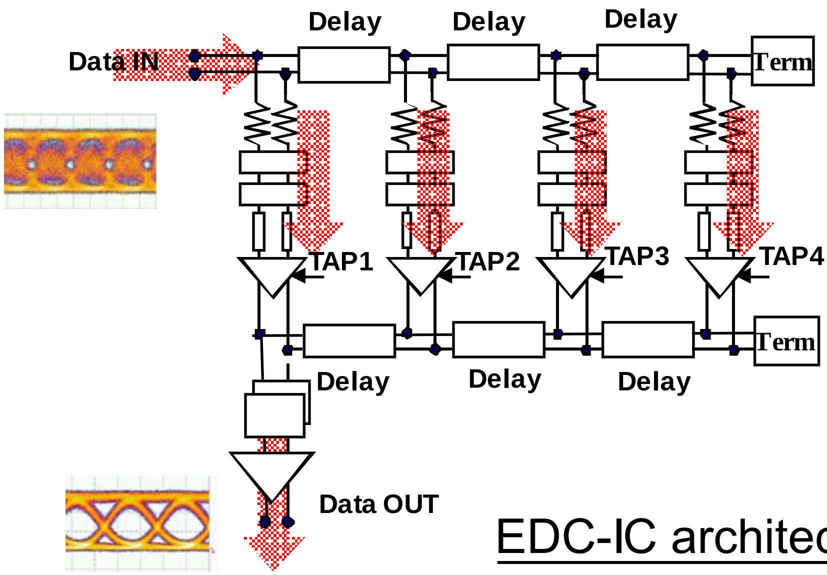


Square-law detection
⇒ nonlinear process

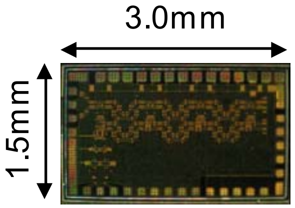


Example: 40Gb/s EDC for PMD compensation [6]

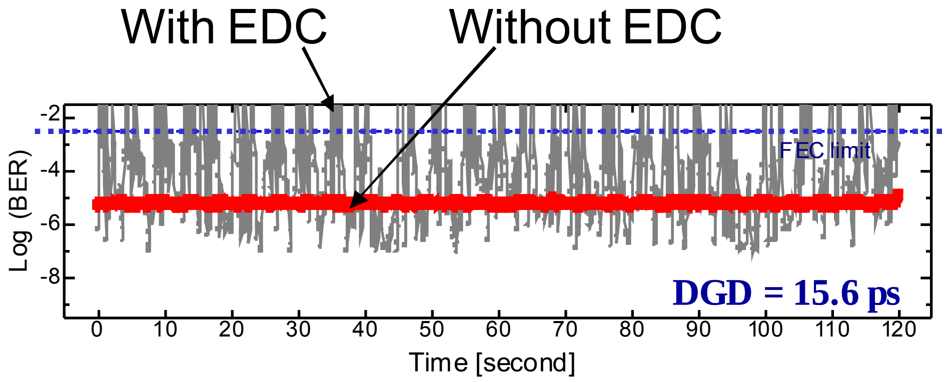
- Electrical equalization IC for PMD-induced waveform distortion compensation
- Feed Forward Equalizer architecture
- InP-HBT Process technology



EDC-IC architecture

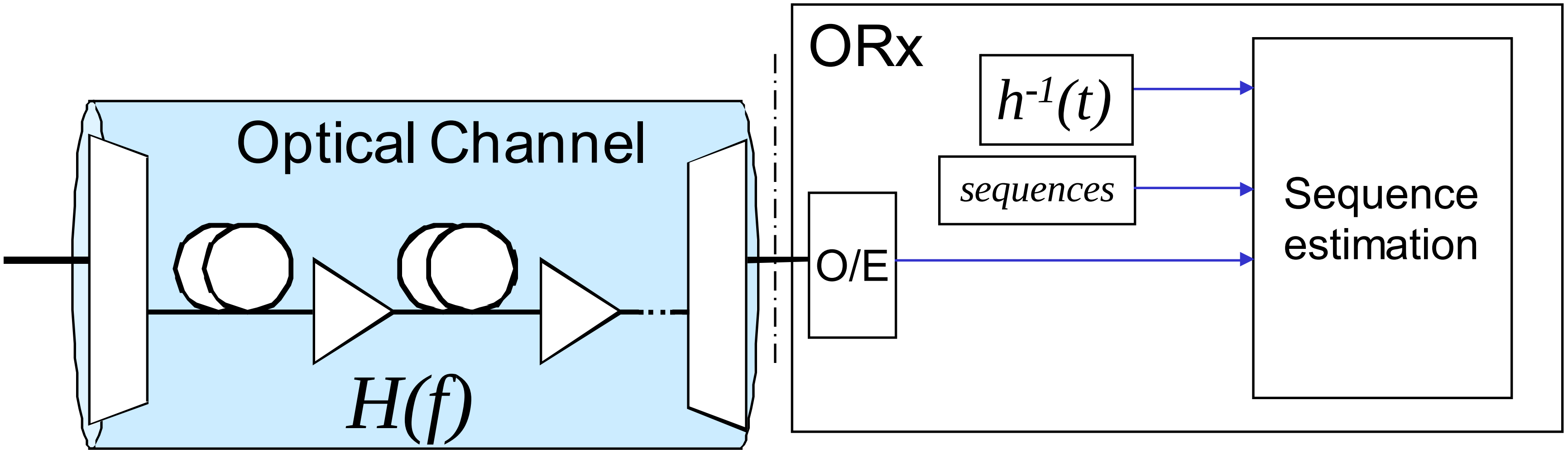


EDC-IC chip



400km transmission experiment

Most-Likely Sequence Estimation



Optical Channel

$H(f)$

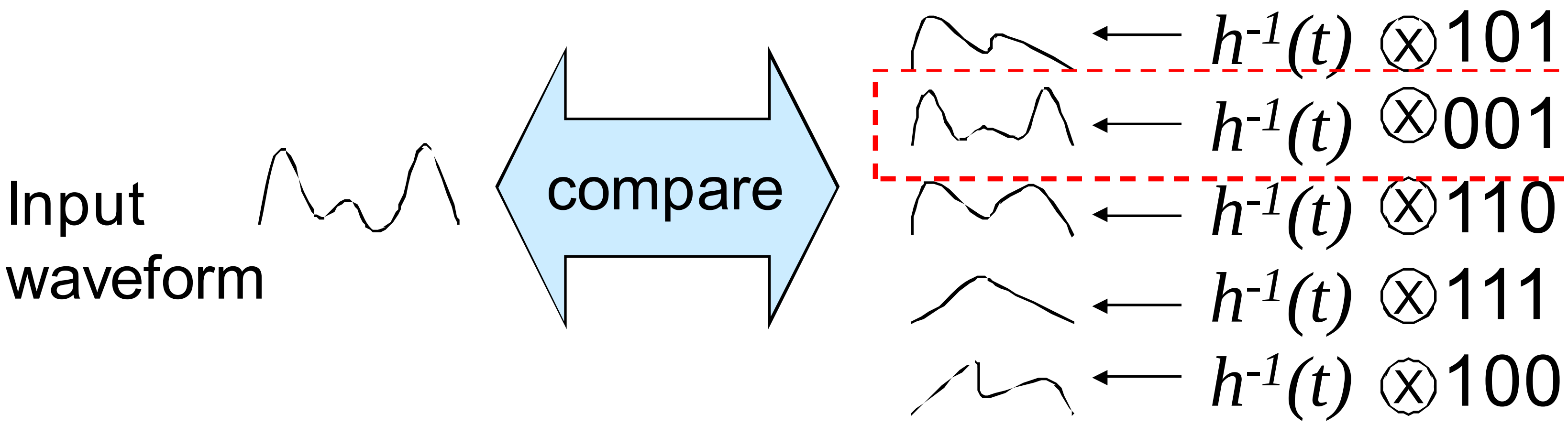
ORx

O/E

$h^{-1}(t)$

sequences

Sequence estimation



Input waveform

compare

$h^{-1}(t) \otimes 101$

$h^{-1}(t) \otimes 001$

$h^{-1}(t) \otimes 110$

$h^{-1}(t) \otimes 111$

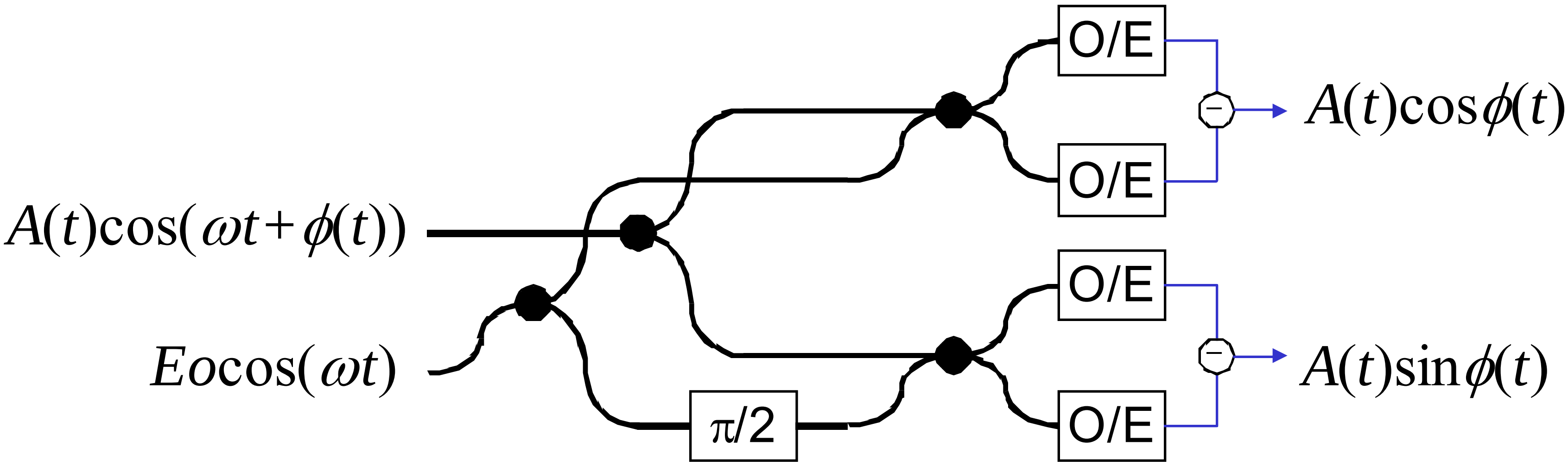
$h^{-1}(t) \otimes 100$

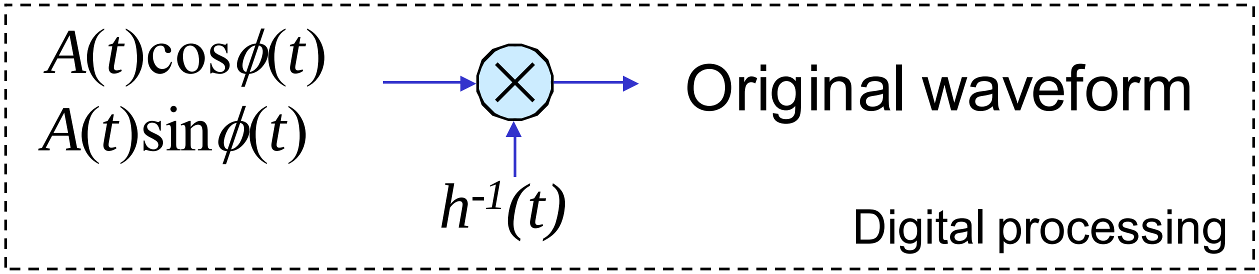
Merits and Demerits of receiver-side equalization

- Merit
  - Fast adaptation possible (local feedback inside ORx)
  - Electrical implementation applicable
- Demerits
  - Perfect equalization difficult
  - Need large-scale, complex signal processing

Coherent detection for advanced receiver-side

Coherent Detection: possible to extract phase information of the optical signal





Technologies Requirement

- Ultra-high speed Digital Processing
- High-speed A/D converter, D/A converter
- Algorithm for optimal equalization
- Signal monitoring

Recent results in advanced equalization

Conference	Paper No.	Affiliation	bitrate	Modulation format and other features
OFC ’05	OThJ2	Univ. college London	10Gb/s	Pre-equalization simulation study
OFC ’05	PDP27	Nortel	10Gb/s	electrical pre-equalization, 5100km
OFC ’05	OThJ4	Marconi/Core Optics	10.7Gb/s	MLSE receiver with duobinary modulation format
ECOC ‘05	Tu3.2.2	Lucent	-	Electrical pre-equalization for fiber nonlinearity (invited talk)
ECOC ‘05	Tu4.2.3	Univ. Kiel	10Gb/s	Receiver side equalization study with duobinary
OFC ‘06	JThB5	Corning	10.7Gb/s	MLSE EDC receiver
OFC ‘06	OWB3	Univ. college London	-	Electrical pre-equalization for fiber review
OFC ‘06	OWB1	Lucent	10.7Gb/s	Electrical pre-equalization for fiber nonlinearity
ECOC ‘06	Th2.5.6	AT&T/Nortel	10Gb/s	electrical pre-equalization, 1600km transmission
ECOC ‘06	Th2.5.5	Univ. college London	40Gb/s	Coherent detection and Rx equalization after 2,480km SMF transmission by electronics
ECOC ‘06	Th4.3.3	CoreOptics	43Gb/s	RZ-QPSK over 100km, polarization MUX

Summary

- Various technologies for data coding is reviewed
  - Modulation format: ASK(NRZ/RZ/CS-RZ), PSK, FSK, combinations
  - Forward Error Correction codes: Reed Solomon, Turbo codes, LDPC
  - Advanced equalization: pre-compensation, receiver side adaptive equalization
- Combination of those technologies will enable higher performance of future submarine cable systems

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6. Shigeki Wada, Risato Ohhira, Toshiharu Ito, Jin Yamazaki, Yasushi Amamiya, Hitoshi Takeshita, Arihide Noda, Kiyoshi Fukuchi “Compensation for PMD-Induced Time-Variant Waveform Distortions in 43-Gbit/s NRZ Transmission by Ultra-Wideband Electrical Equalizer Module”, OFC2006, paper OWE2, 2006

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