Investigation of FEC Codes and Time-Diversity on Experimental FSO LEO-to-Ground Channels

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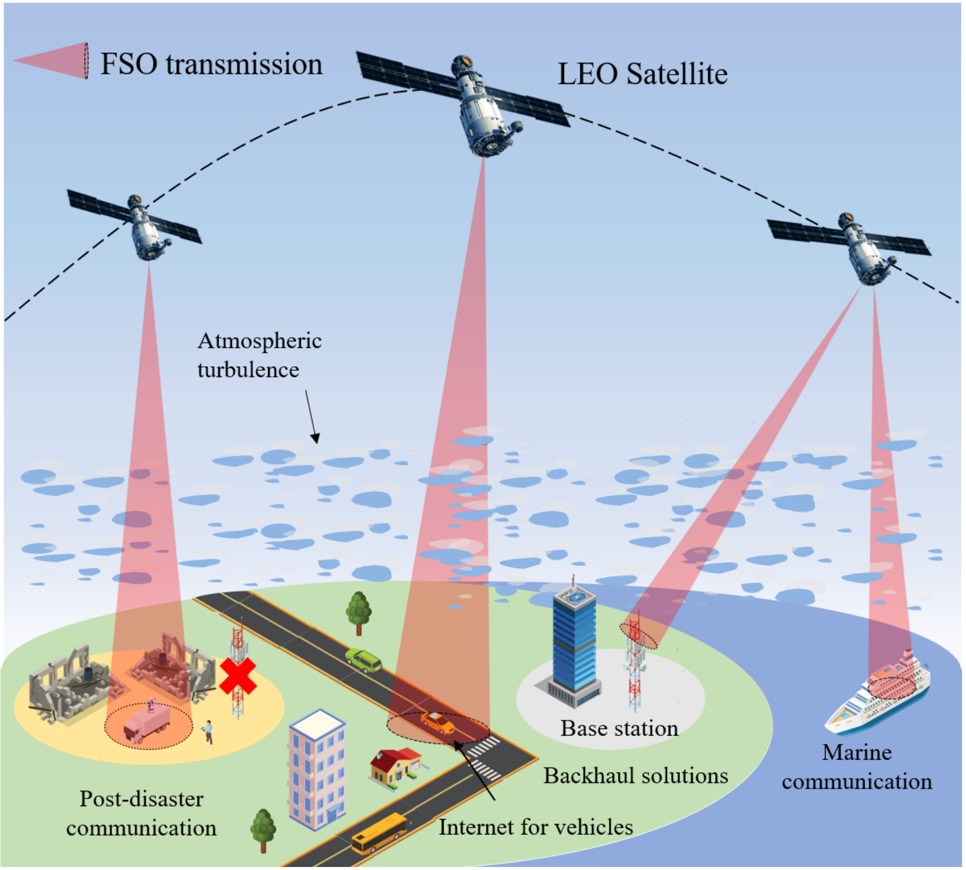
Outline

I. Introduction

II. Simulation Model & Result

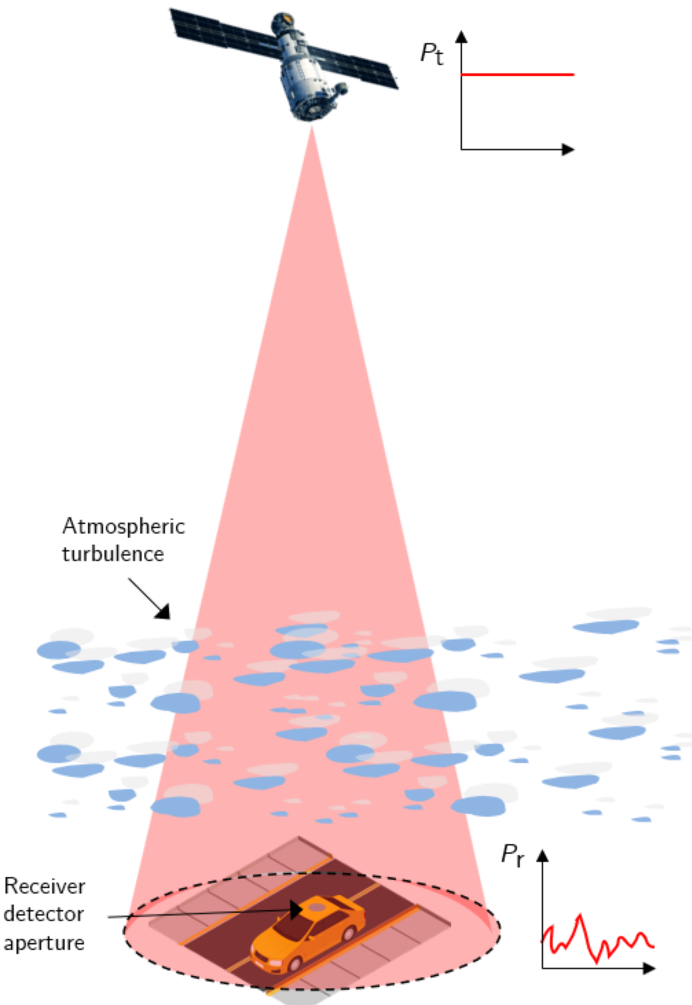
Free-Space Optics (FSO)-Based Satellite Systems

- **Free-space Optics (FSO):**
  - Infrared wavelength (700-1600 nm)
  - Extremely high data rate (~ Gbps or even Tbps) thanks to a wide range of unlicensed bandwidth
- **Low-earth Orbit (LEO) Satellite**
  - Global coverage via constellation network
  - Lower latency compared to other types of satellites



With extremely high data rates and global coverage, the FSO-based LEO satellite system is a promising architecture for beyond-5G networks.

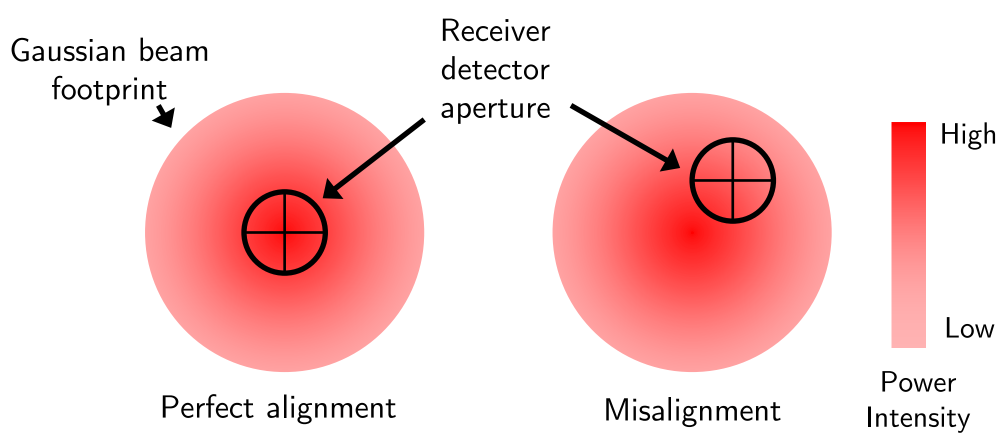
Challenging Issues: Fading Channel



1. Atmospheric Turbulence:
   - **Cause**: Inhomogeneity in refractive-index along the propagation path
2. Pointing Error:
   - **Cause**: Misalignment between the center of beam footprint and that of the receiver detector

⇒ *Random power fluctuation at the receiver*

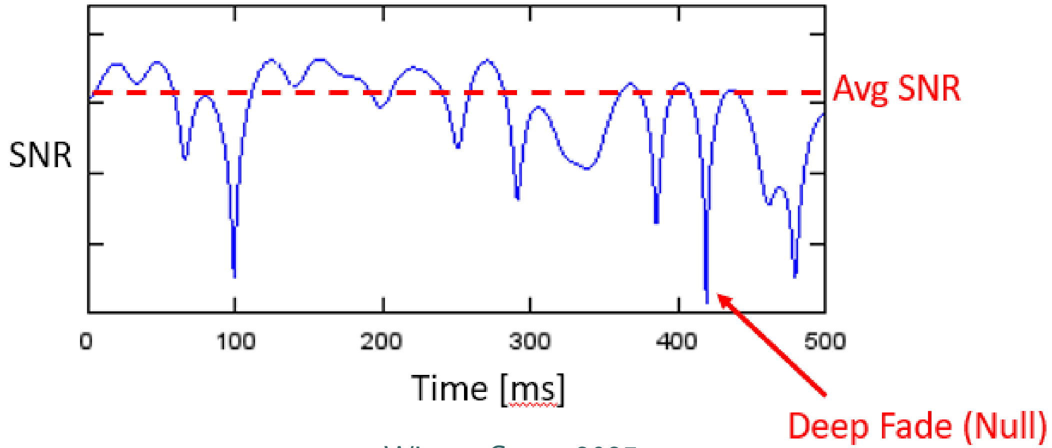
⇒ **Fade mitigation techniques** are required.



Channel Coding for FSO Satellite System

- To mitigate the FSO fading, channel coding or error-correction code (ECC) is one of the indispensable schemes.
- A challenge in channel codes design for optical systems: *Slow fading channel*
  - Long coherence time (in the order of milliseconds) and high data rate (~Gbps) ⇒ If deep fade happens, a wide range of bits will be canceled out.
  - E.g., Coherence time: 1 ms, data rate: 1 Gbps => The fading remains constant over 10^6 consecutive bits.

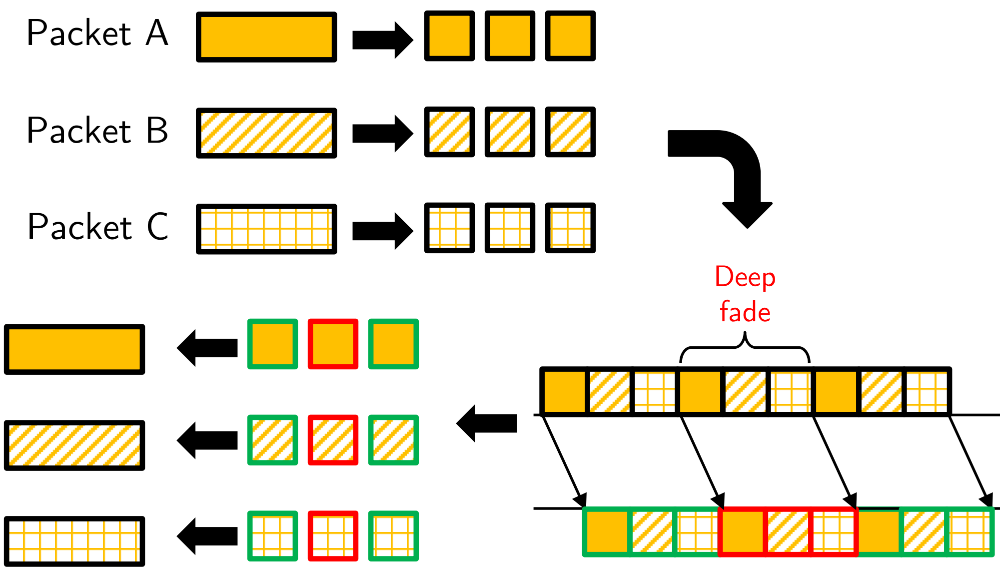
  => A large amount of parity bits is needed to ensure the system's reliability, which is ineffective and may be infeasible.



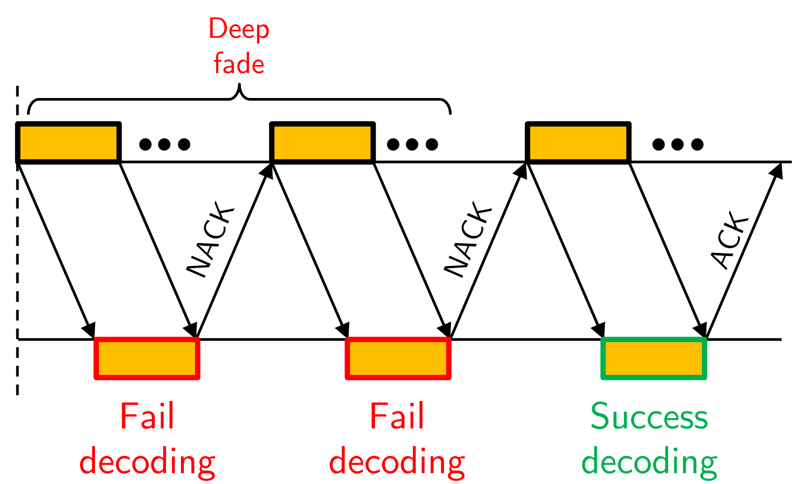
Possible Solution: Temporal Diversity Techniques

- To enhance the performance of ECC codes over a slow fading channel, an efficient solution to exploit the *temporal diversity of the channel*.
  - **Temporal diversity** refers to fade mitigation techniques, in which data is transmitted multiple times at different points in time.
- There are two main methods: (1) Interleaver, and (2) Hybrid Automatic Repeat Request (HARQ)

Interleaver + ECC



Hybrid ARQ (ARQ + ECC)



Literature Review: ECC & Time-diversity Techniques

Literature review of ECC and time-diversity techniques investigation for satellite optical channels.

Works	Time-diversity Techniques		Considered ECC Codes	Remarks
	HARQ	Interleaver		
IEICE Trans. COM 2012		✓	Non-binary staircase low-density generator matrix (LDGM) code	Propose a non-binary staircase LDGM code for the Marokov-based satellite-to-ground FSO channel model
ICSOS 2014			Luby transform (LT), systematic LT (SLT), LDGM codes	Investigate the performance of different ECC and interleaver
ICSO 2018		✓	Various types of low-density parity check (LDPC) codes	Present a simulation framework to compare different ECC codes
Optics Comm. 2019		✓	802.11n LDPC	Investigate the performance of LDPC code and block interleaver
ICICAS 2019	✓	✓	LDPC codes (details are not provided)	Investigate the performance of chase combining (CC)-HARQ and interleaver
IEEE Trans. Veh. Tech. 2022	✓		Rate-compatible punctured convolutional (RCPC) codes	Propose a design of incremental redundancy (IR)-HARQ based sliding window mechanism
IEEE Trans. Aerosp. Electron. Syst. 2024	✓		Protograph-based Raptor-like (PBRL) LDPC codes	Propose a mathematical framework for PBRL-based IR-HARQ design

Motivations & Contributions

- In practical system design, it is crucial to understand the strengths and weaknesses of each methods so that we can identify most efficient option for a specific need.

=> *It is necessary to have a performance comparison among these designs across relevant metrics.*

- *However, the performance comparisons these designs have not been investigated in the literature.*

- Main contributions:
  - Compare and investigate the performance of different designs based on ECC code and time-diversity techniques
  - Provide design guidelines and insightful discussions for practical design

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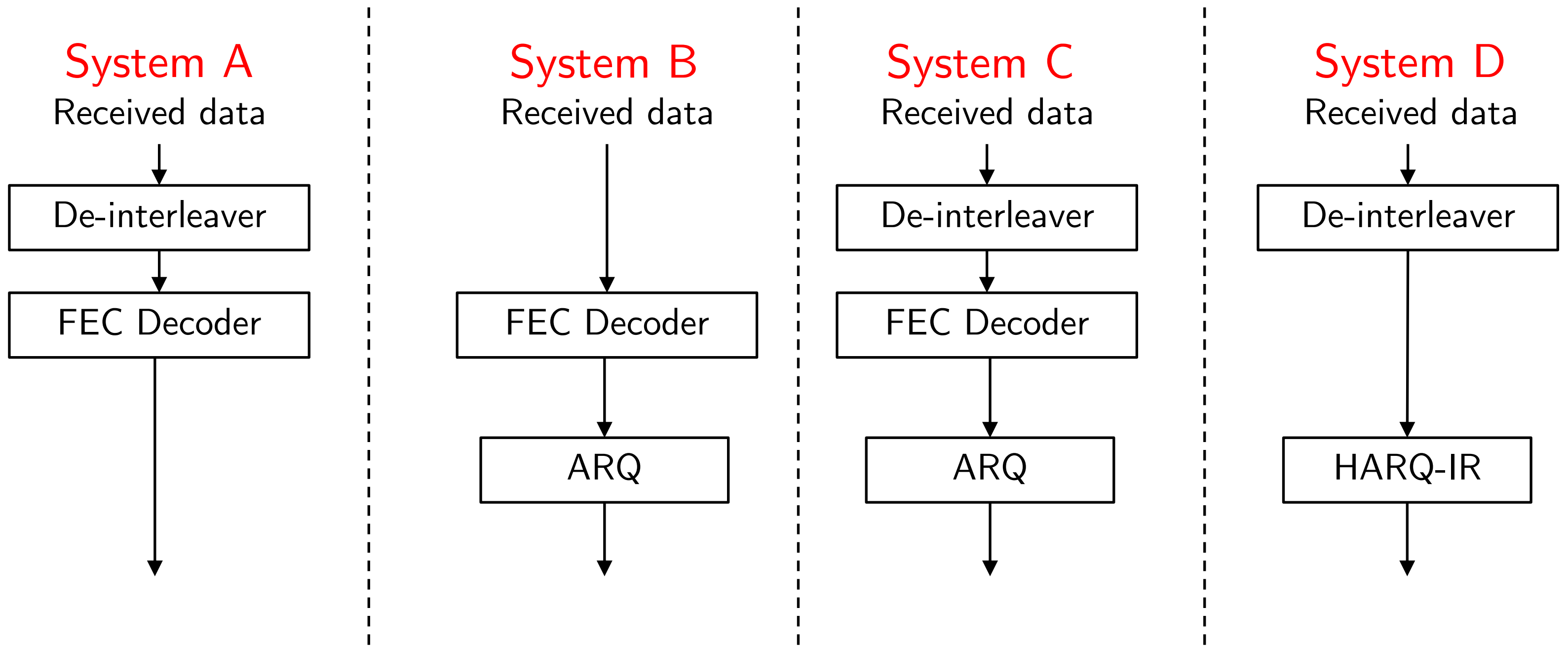
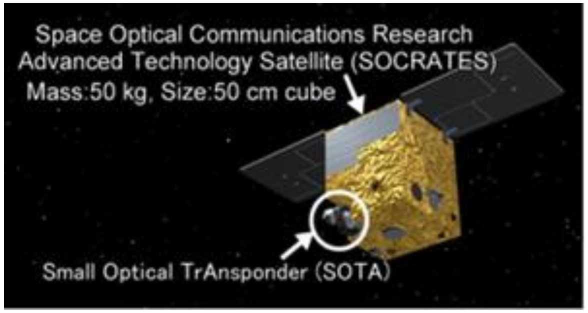
Overview of Considered Systems

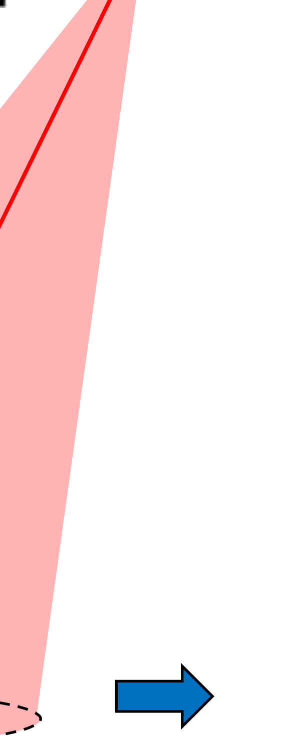
- We consider four different systems which are the combination of ECC, interleaver, and ARQ
- The evaluation is simulated over recorded channel gains from the SOTA experiment provided by NICT.
- Performance metrics: outage probability, goodput, and average number of decoding iterations (for LDPC codes)



Experiment Overview

Microsatellite
SOCRATES





Optical ground stations
(OGS) at Koganei

- Low-earth orbit (LEO) satellite-to-ground laser-communication.
- Optical signals from the SOTA is transmitted to the OGS at at Koganei, Tokyo.
- The data was recorded at both OGS, which are around 10 meters apart.
- Date of experiment: April 5 and May 5, 2016
- Wavelength: 1550 nm

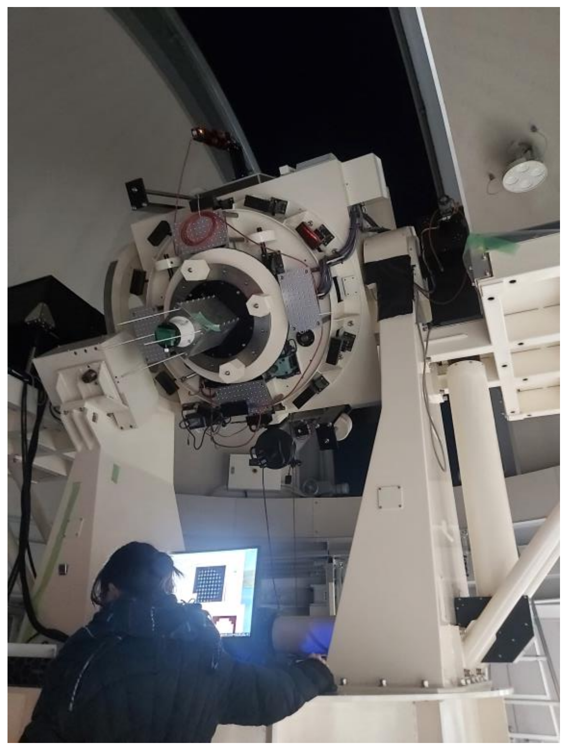
OGS with 1-meter telescope

OGS with 1.5-meter telescope

Experiment Overview (cont.)

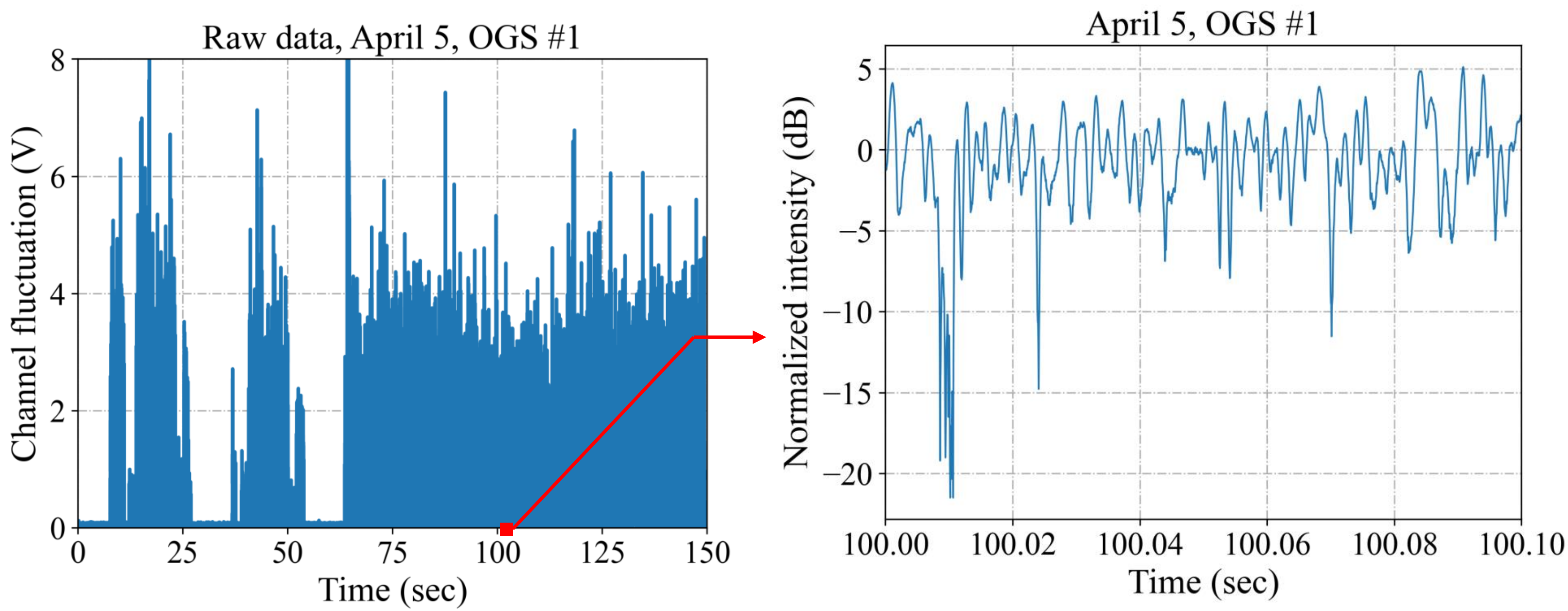
- The data is recorded using 5-cm receivers aperture mounted on the 1/1.5-meter telescopes.
- Sampling rate: 20 kHz
- Recorded time: 150 seconds
- Beam divergence full-angle: 223 μrad => Beam footprint diameter is 130 meters.

1.5-meter telescope from outside



Data Overview

- Four datasets: April 5th and May 5th on two OGS



Plot of raw dataset sota20160405_105 versus time.

Simulation Model

- We assume a discrete-time channel model in which the received data symbol y_i at time i is given as

$$y_i = h_i x_i + n_i,$$

where

- x_i is the On-Off Keying (OOK)-modulated symbol (normalized to $\{0, 1\}$)
- n_i is the additive white Gaussian noise (AWGN)
- h_i is the channel coefficient taken from the experimental records. h_i is blockwise for T_{B} consecutive symbols, where

$$T_{\mathrm{B}} = \frac{\text{channel sampling time}}{\text{symbol time}}.$$

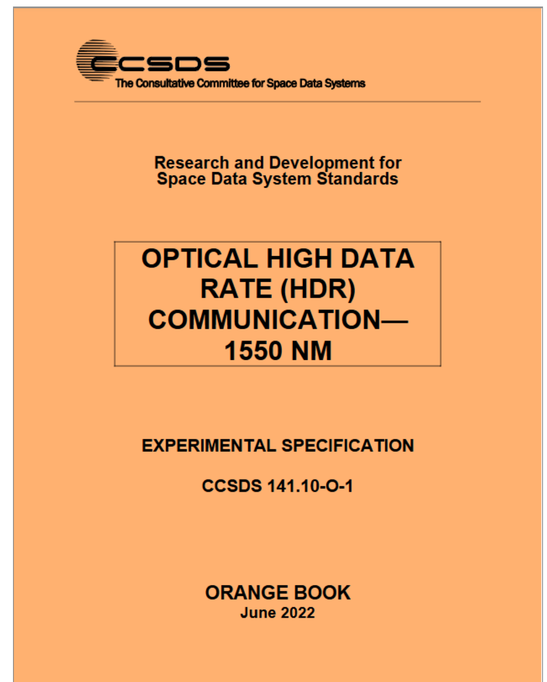
Considered ECCs: DVB-S2

- Two ECCs are considered: DVB-S2 LDPC code and 5G NR LDPC code

(1) DVB-S2 LDPC code:

- DVB-S2(Digital Video Broadcasting - Satellite - Second Generation) is a standard, that is primarily adopted for satellite television broadcasting systems
- DVB-S2 channel code standard: BCH (outer code) + LDPC code (inner code)

- DVB-S2 is recommended *in the orange book of Consultative Committee for Space Data Systems (CCSDS) for optical space-to-ground links*
  - CCSDS: an international forum of by the major space agencies around the world (e.g., NASA, JAXA, etc.)
  - Aim to develop standards for space data systems and communications.
  - Orange book: document experimental work that does not yet have consensus of enough member agencies to standardize.


CCSDS
The Consultative Committee for Space Data Systems

Research and Development for
Space Data System Standards

OPTICAL HIGH DATA RATE (HDR) COMMUNICATION—1550 NM

EXPERIMENTAL SPECIFICATION

CCSDS 141.10-O-1

ORANGE BOOK
June 2022

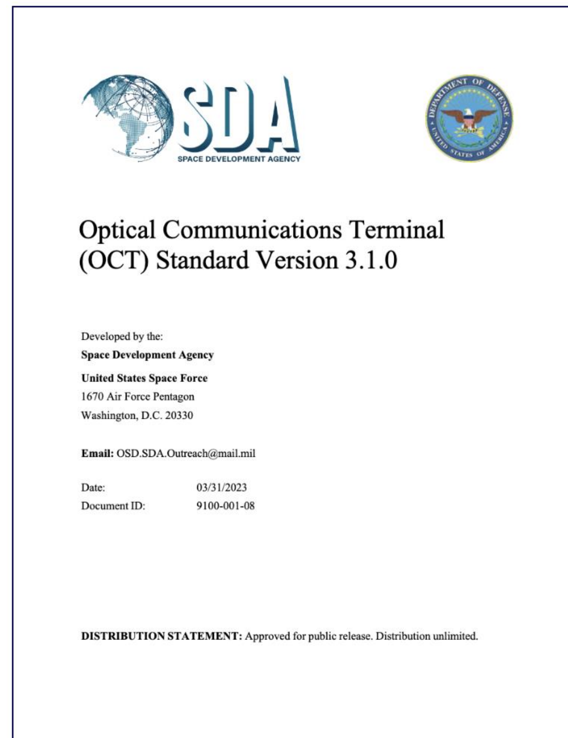
Considered ECC: 5G NR LDPC

(2) 5G NR LDPC code:

- 5G NR LDPC: type of LDPC codes used in the 3GPP 5G New Radio standard
- Compared to LDPC codes of DVB-S2:
  - Support rate-compatible for IR-HARQ
  - Support wide range of block length

○ 5G NR LDPC is used *in the Optical Communication Terminal (OCT) Standard by the Space Development Agency (SDA) for optical space-to-ground links*

- SDA (formed in 2019) is managed by U.S. Space Force
- OCT standard is their own effort to standardize the optical satellite communication systems
- Current version: OCT 3.1.0 (released in 2023), they are working on version 4.0



SDA
SPACE DEVELOPMENT AGENCY

Optical Communications Terminal (OCT) Standard Version 3.1.0

Developed by the:
Space Development Agency
United States Space Force
1670 Air Force Pentagon
Washington, D.C. 20330

Email: OSD.SDA.Outreach@mail.mil

Date: 03/31/2023
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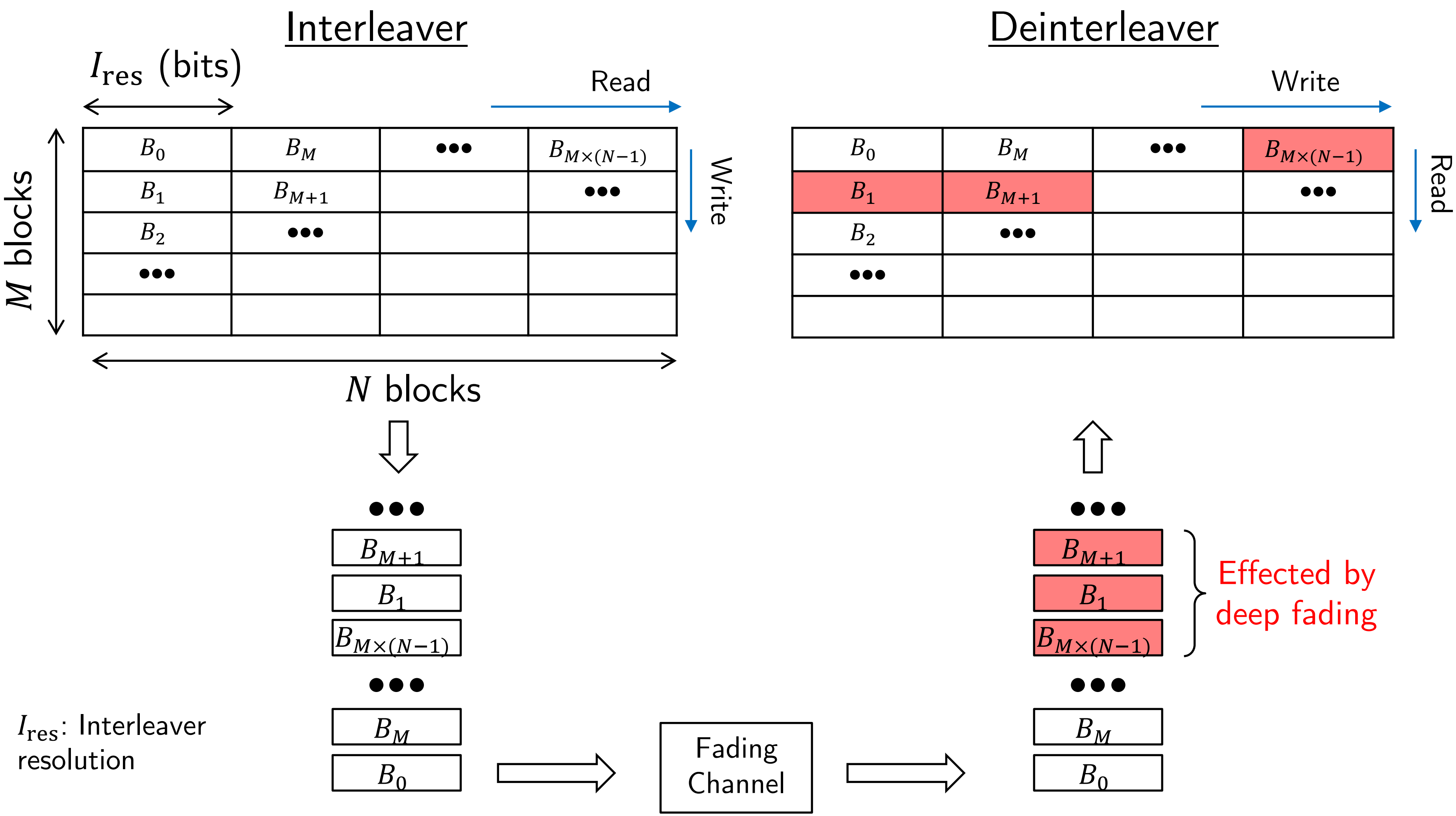
Block Interleaver

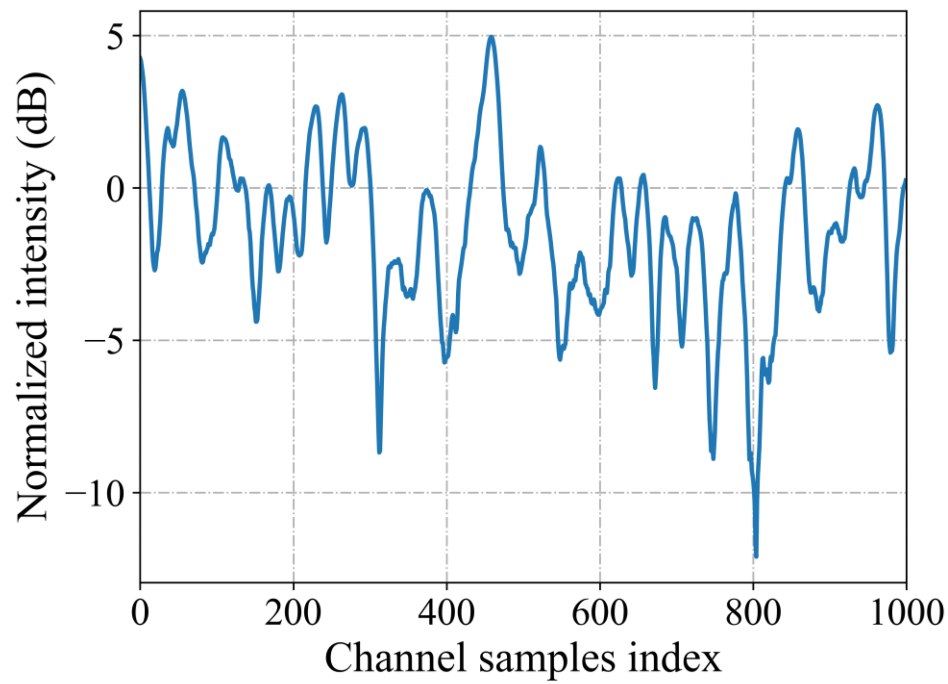
- Block interleaver is considered for the system



I_{res}: Interleaver resolution

Simulation Scenario & Parameters

- Consider 1000 samples ($\sim$ 50 ms)
- Channel coherence time: 0.55 ms
- Interleaver parameters: $I_{\text{res}} = 8$ (bits), $N = 100$ frames
- DVB-S2 LDPC code: $R = 4/9$, coded frame length $N_{\text{frame}} =$ 16200 bits
- 5G NR LDPC code: $R = 1/2$, $N_{\text{frame}} = 16936$ bits
- Maximum number of iterations: 100
- Performance metric: outage probability



$$\text{outage probability} = \frac{\#\text{ of unsuccessfully decoded frames}}{\#\text{ of transmitted frames}}$$