

Master's Thesis Presentation

Design of Retransmission Protocol Based on Low-Density Parity Check Code for Optical Satellite Systems

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Outline

I. Introduction

II. System Description

III. Results & Discussions

IV. Conclusion

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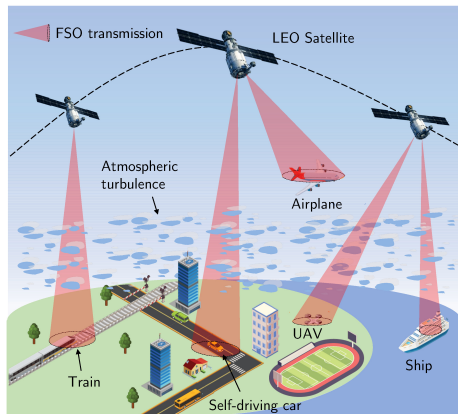
Free-Space Optics (FSO)-Based Satellite Systems

■ Free-space Optics (FSO):

- Infrared wavelength (700-1600 nm)
- **Extremely high data rate** (\sim Gbps or even Tbps) thanks to a wide range of unlicensed bandwidth

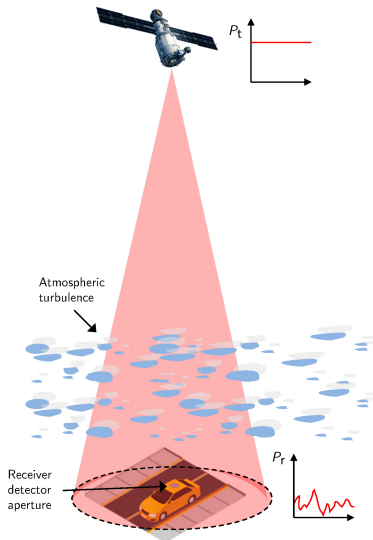
■ Low-earth Orbit (LEO) Satellite

- 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: Uncertainty Channel



1. Atmospheric Turbulence:

Cause: Inhomogeneity in refractive-index along the propagation path of the optical signal

2. Atmospheric Attenuation:

Cause: The molecular absorption and aerosol scattering

3. Beam-spreading Loss:

Cause: Geometric spread of the beam footprint at the receiver

*The received signal is degraded, which results in **unreliable transmission** \implies Mitigation techniques are required.*

Error-Control Solutions

In general, common link-layer approaches are **automatic repeat requests (ARQ)**, **error-correction codes (ECC)**, and **hybrid ARQ (HARQ)**

In the context of *optical satellite systems*,

- **ARQ** require retransmissions \implies *Increase the latency over noisy channels, especially in satellite systems.*
- **ECC** adds redundancy to correct errors \implies *May lead to inefficient throughput when the channel is in good condition.*
 \implies **ARQ** and **ECC** may be *inefficient in time-varying optical channels*
- **Hybrid ARQ (HARQ)**, which is the combination of ARQ and ECC, is a *potential approach*
 - Among other HARQ variants, **Incremental Redundancy (IR)-HARQ** is the most efficient one over the time-varying FSO channels [1].
 - **IR-HARQ** transmits additional parity bits when the frame is uncorrectable.

[1] Hoang D. Le and Anh T. Pham, "Link-Layer Retransmission-based Error-Control Protocols in FSO Communications: A Survey," *IEEE Commun. Surv. Tutor.*, Third Quar. 2022.

Literature Review

- Several studies have addressed the design of IR-HARQ for optical satellite systems [1, 2, 3].
- These designs focused on either **Reed-Solomon** or **convolutional punctured code**.
- However, the performance of RS/convolutional codes over FSO channels **still shows a considerable gap to the theoretical limits** [4, 5].



The performance of IR-HARQ in optical satellite systems can be further improved by using a proper design of ECC

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- [1] Hoang D. Le *et al.*, "Throughput and delay performance of cooperative HARQ in satellite-HAP-vehicle FSO systems," in *Proc. IEEE Veh. Technol. Conf. (VTC-Fall)*, Sept. 2021.
 - [2] Hoang D. Le and Anh T. Pham, "On the design of FSO-based satellite systems using incremental redundancy hybrid ARQ protocols with rate adaptation," *IEEE Trans. Veh. Technol.*, Jan. 2022.
 - [3] Hoang D. Le *et al.*, "FSO-based space-air-ground integrated vehicular networks: Cooperative HARQ with rate adaptation," *IEEE Trans. Aerosp. Electron. Syst.*, Aug. 2023.
 - [4] J. Anguita *et al.*, "Shannon capacities and error-correction codes for optical atmospheric turbulent channels," *J. Opt. Commun. Netw.*, Sept. 2005.
 - [5] Gappmair and M. Flohberger, "Error performance of coded FSO links in turbulent atmosphere modeled by gamma-gamma distributions," *IEEE Trans. Wireless Commun.*, May 2009.

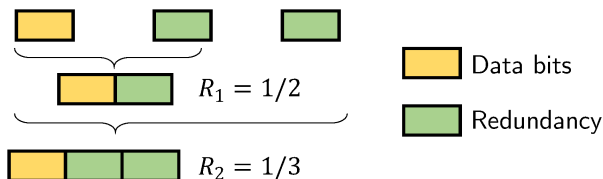
Rate-compatible (RC) Low-density Parity-check (LDPC) Code

A possible approach for ECC is the **low-density parity-check (LDPC) code**.

- Capacity-approaching performance and low-decoding complexity

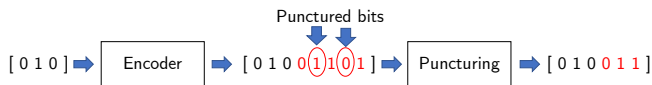
To apply the LDPC to the design of IR-HARQ, it is necessary to address the **rate-compatible (RC)-LDPC** code family.

- A low-rate coded frame can be constructed by *adding redundancy to a higher-rate coded frames*



Rate-compatible (RC)-LDPC Code (cont.)

1. **Puncturing:** Selected bits are removed from an encoded frame to obtain a frame with a higher code rate



Limitation: Performance degradation of higher-rate codes

2. **Code extension:** Extend the parity check matrix of a higher-rate code to obtain that of lower-rate codes \implies *A potential approach*

$$H_{1/3} = \begin{array}{|c|c|} \hline H_{1/2} & 0 \\ \hline \hline \hline \end{array}$$

Main Contributions

1. Address the IR-HARQ design based on RC-LDPC code extension for optical LEO satellite systems.
2. Assess the performance of the design proposal in terms of goodput, energy efficiency, and average frame delay.
3. Consider a practical scenario with LEO satellites' real data and the moving vehicle's positions to estimate the system performance accurately

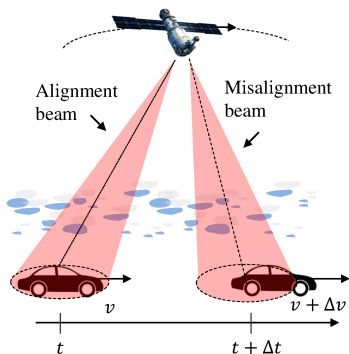
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System Model



System model: Optical downlink channel from an LEO satellite to a ground vehicle

FSO Channel Model:

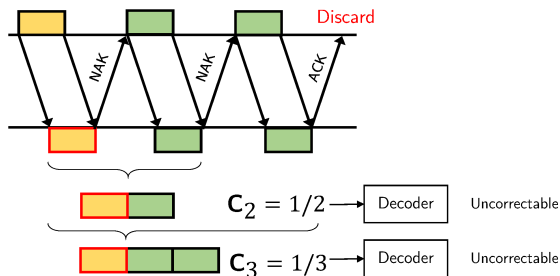
- Turbulence Fading
- Turbulence Attenuation
- Pointing Error
 - The vibration of the satellite
 - The sudden change in vehicle's velocity over a short period of time

Considered Link-layer Solution: IR-HARQ based on RC-LDPC Code Extension with Burst Transmission

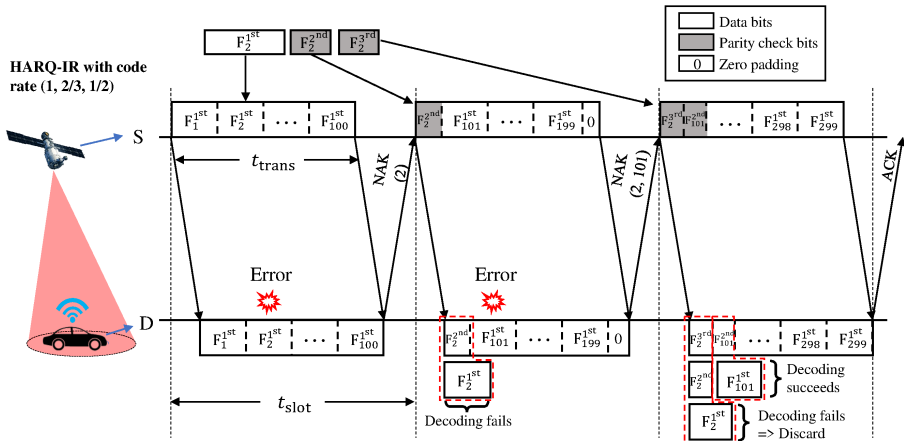
IR-HARQ based on RC-LDPC Code Extension

- When a frame is corrupted/uncorrectable, its redundancy will be transmitted
- The number of code rates in the family corresponds to the number of transmission rounds, N_r
- A frame is discarded when it is uncorrectable after the maximum number of transmission rounds

Example: IR-HARQ with a systematic RC-LDPC code family $(1, 1/2, 1/3)$, $N_r = 3$



Proposed Design



- Fixed-size time-slotted structure
- If a frame is corrupted/uncorrectable, its redundancy will be transmitted **in the next burst**

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Considered Practical Scenario

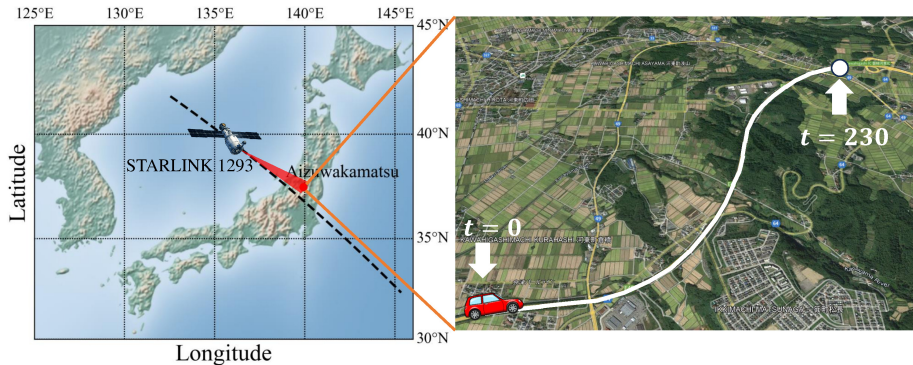


Figure: Illustration of LEO satellite pass over Japan (left image) and the self-driving car moving during the satellite pass duration (right image) on 23 December 2021, 16:09:20:00 UTC+9.

System Parameters

Name	Symbol	Value
LEO Satellite (Transmitter)		
Divergence half-angle	θ	20 μ rad
Bit rate	R_b	1 Gbps
Burst duration	t_{burst}	6 ms
Optical wavelength	λ	1550 nm
Jitter angle	θ_{jt}	2 μ rad
Vehicle (Receiver)		
Vehicle altitude	H_v	1.5 m
Aperture radius	r_a	5 cm
Noise standard deviation	σ_n	10^{-7} A/Hz
Detector responsivity	\mathfrak{R}	0.9
Other Parameters		
Atmospheric altitude	H_a	20 km
Rms wind speed	w_{wind}	21 m/s
Ground turbulence level	$C_n^2(0)$	10^{-14} m ^{-2/3}
Data frame size	N_d	1500 bytes
Vertical extent of cloud	H_c	2 km
Cloud liquid water content	M_c	1 mg/m ³
Cloud droplet number concentration	N_c	250 cm ⁻³

1. **Goodput:** The successfully transmitted data bits per second

$$\text{Goodput} = \frac{\# \text{ of successfully transmitted data bits}}{\text{Simulated time}}$$

2. **Energy Efficiency:** The successfully transmitted data bits per joule

$$\text{Energy Efficiency} = \frac{\text{Goodput}}{\text{Transmitted power}}$$

3. **Average frame delay:** The average number of time slots required for a frame to be transmitted successfully

Comparison among Link-layer Solutions

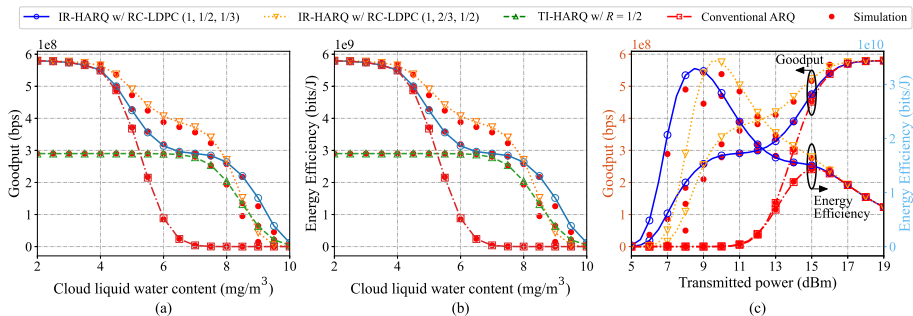


Figure: (a) Goodput and (b) energy efficiency performance comparison of different link-layer solutions over CLWC, and (c) its tradeoff.

- IR-HARQ outperforms TI-HARQ and ARQ in terms of goodput and energy efficiency.
- The trade-off between energy efficiency and goodput.

Performance over the Satellite Pass Duration

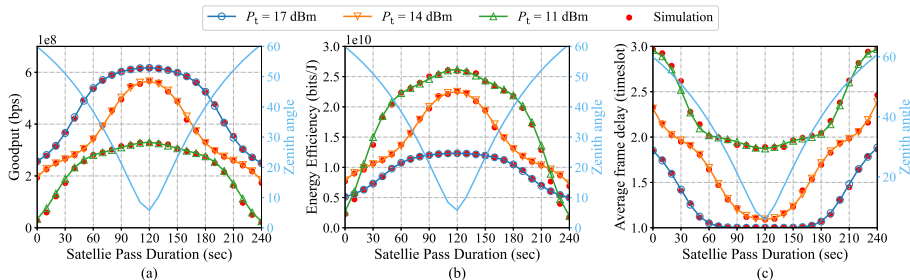


Figure: (a) Goodput, (b) energy efficiency, and (c) average frame delay of the IR-HARQ-based RC-LDPC (1, 1/2, 1/3) over a satellite pass duration for different LEO transmitted powers.

- Higher transmitted power \implies higher goodput and lower delay performance but may lead to lower energy efficiency
- The transmitted power should be selected to maintain specific levels of performance metrics

Convergence Analysis of Decoding Algorithm

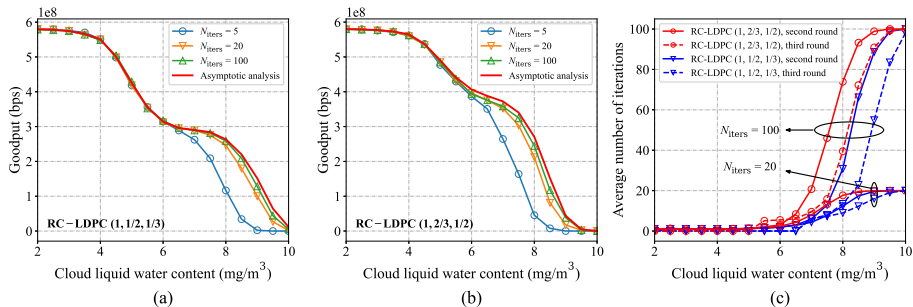


Figure: (a & b) Goodput performance and (c) the average number of iterations of the IR-HARQ-based RC-LDPC over CLWC with different maximum numbers of iterations (N_{iters}).

- The impact of N_{iters} becomes clear when CLWC values are high, i.e., $M_c > 6 \text{ mg/m}^3$
- N_{iters} can be selected to maintain specific levels of goodput and the average numbers of decoding iterations.

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Conclusion

1. Considered an IR-HARQ-based LDPC code extension design for optical satellite systems
2. Highlighted the effectiveness of the proposal compared to conventional approaches
3. Discussed the proper selection of transmitted power for the considered system

Published/In Revision Papers

- [1] **Cuong T. Nguyen**, Hoang D. Le, Chuyen T. Nguyen, and Anh T. Pham, "Toward Practical HARQ-Based RC-LDPC Design for Optical Satellite-Assisted Vehicular Networks," *IEEE Transactions on Aerospace and Electronic Systems*, Sept. 2023 (Submitted)
- [2] **Cuong T. Nguyen**, Hoang D. Le, and Anh T. Pham, "Performance of IR-HARQ-based RC-LDPC Code Extension in Optical Satellite Systems," in *Proc. VTS Asia-Pacific Wireless Communications Symposium (APWCS)*, Tainan, Taiwan, Aug. 2023.

Award

- *IEEE VTS Tokyo/Japan Chapter APWCS Young Researcher's Encouragement Award* for the paper accepted in APWCS 2023

Thank you for your attention!