Performance of IR-HARQ-based LDPC Extension Codes in Optical Satellite Systems

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Outline

I. Introduction

II. System Description

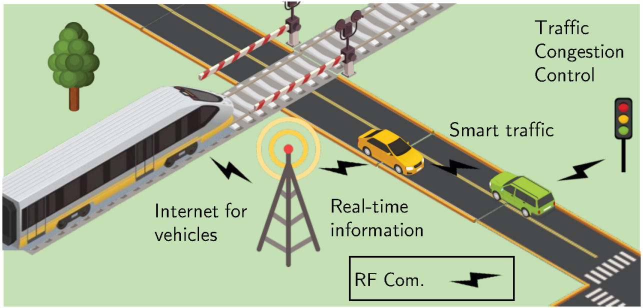
III. Results & Discussions

Internet of Vehicles (IoVs)

Internet of Vehicles (IoVs): The network of vehicles and related entities

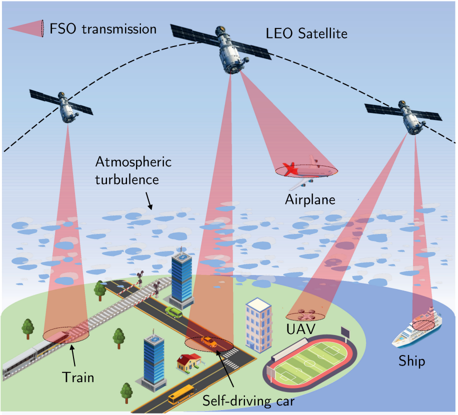
- The current network supporting IoV may face two limitations

1. Radio-frequency (RF) spectrum scarcity ⟹ Restricted data rate (Mbps or lower)
2. Limited coverage of terrestrial infrastructure ⟹ Cannot enable ubiquitous connections



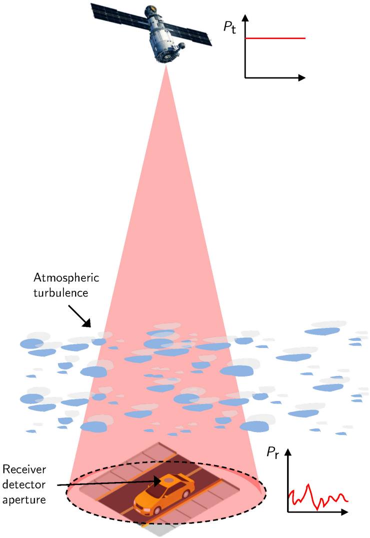
Optical Satellite-Assisted IoV

1. **Data rate solution:** Free-space Optical (FSO) Commun.
    - Infrared wavelength (700-1600 nm)
    - Higher data rate ($\sim$ Gbps or even Tbps) thanks to a vast range of unlicensed bandwidth
2. **Coverage solution:** Low-earth orbits (LEO) Satellites
    - Altitude: $\leq$ 2000km
    - Low latency compared to other types of satellites
    - Global coverage



Optical LEO-satellite communication is promised to become an enabling technology for the future applications of the IoVs.

Challenging Issues: Unreliable Transmission



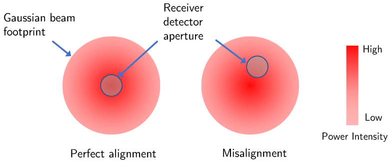
1. **Atmospheric Turbulence**

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

2. **Pointing Misalignment**

Cause: Misalignment between the center of the beam footprint and the center of the receiver detector

➡ The power of the received signal is strongly fluctuated, which results in unreliable transmission.

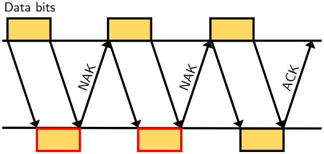


Possible Solutions: Reliable Trans. Protocols

Possible solutions: Automatic Repeat Request (ARQ), **Error Correction Code (ECC)**, and **Hybrid ARQ**

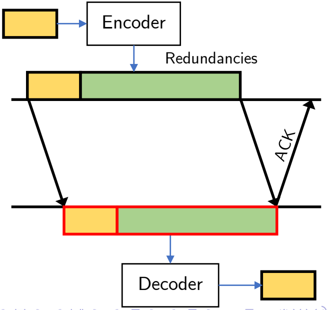
1. **Automatic Repeat Request (ARQ):**

- Retransmit frame when it is erroneous
- May not be efficient as it requires many retransmissions when the channel is deep fading $\implies$ High latency



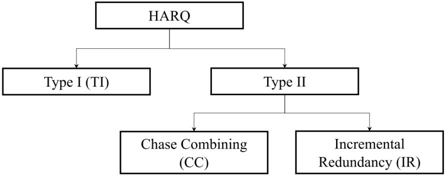
2. **Error Correction Code (ECC):**

- Add redundancy to correct a number of errors at the receiver
- May not be efficient as the redundancy is always transmitted $\implies$ Lower throughput when the channel condition is good



Possible Solutions: Reliable Trans. Protocols (Cont.)

3. **Hybrid ARQ:** Combination of ARQ and ECC



Type-I (TI)-HARQ:

- Transmit the same encoded frame every round

Chase Combining (CC)-HARQ:

- Combining a number of encoded frames in a single frame based on a maximum likelihood criterion

Disadvantages: TI- and CC-HARQ transmit encoded frames every round $\Longrightarrow$ Lower throughput when the channel condition is good

Incremental Redundancy (IR)-HARQ:

- Transmits redundancy when data frame gets errors

➡ **IR-HARQ** is a potential candidate for the reliable transmission issue of the considered system.

Literature Review

Currently, there have been some studies addressing the HARQ design for optical satellite systems [1-3].

Error-correction codes of these designs focus on **convolutional code** and **Reed-Solomon code**.

Convolutional code:

- Work on a continuous stream of data bits
- Use the Viterbi algorithm to decode

Reed-Solomon code:

- Symbol-based error correction code
- Constructed based on the theory of Galois fields

[1] Hung D. Nguyen *at el*, "Throughput and delay performance of cooperative HARQ in satellite-HAP vehicle FSO systems," in *Proc. IEEE Veh. Technol. Conf.*, 2021.

[2] Hoang D. Le *at el*, "On the design of FSO-based satellite systems using incremental redundancy hybrid ARQ protocols with rate adaptation," *IEEE Trans. Veh. Technol.*, 2022.

[3] Hoang D. Le *at el*, "Fso-based space-air-ground integrated vehicular networks: Cooperative harq with rate adaptation," *IEEE Trans. Aerosp. Electron. Syst.*, 2023.

Literature Review

One property of the considered system is the preference for long data frames

- Effectively make use of high data rate ($\sim$ Gbps) and long coherent time (in order of milliseconds)

However, the ECCs of the current designs may not be efficient when the data frame is long

- **Convolutional Code:** Long data frames result in exponentially increasing complexity of Viterbi decoder
- **Reed-Solomon Code:** Long Reed-Solomon codes implemented on a large-size Galois field may be infeasible due to the high complexity

➡ It is necessary to have a design of proper ECC

Low-density Parity Check (LDPC) Code

Low-density Parity Check (LDPC) code, which is a class of linear block code with sparse parity check matrix, *show great advantages in long frame length regimes.*

- When the frame length increases, the performance of the LDPC code can *approach Shanon's theoretical limit.*
- Thanks to the spare parity check matrix, it can retain *low decoding complexity when the frame length increases.*

⇒ LDPC code is a potential candidate for considered systems.

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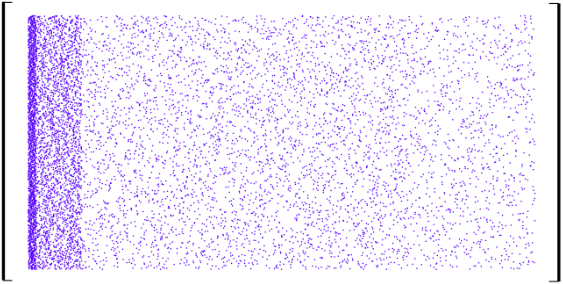
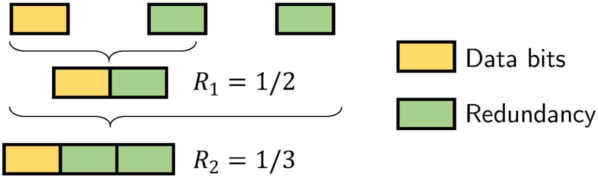


Rate-compatible (RC)-LDPC Code Family (1)

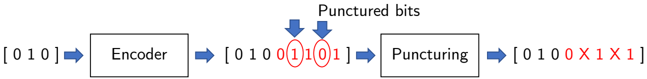
To facilitate the operation of the IR-HARQ, we consider **rate-compatible (RC)-LDPC** code.

- A high code rates are nested in a lower code rate $\implies$ A low-rate coded frame can be constructed by adding redundancy to a higher-rate coded frame
- Allow the change of code rates with only one pair of encoder/decoder $\implies$ Reduce complexity



Rate-compatible (RC)-LDPC Code Family (2)

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

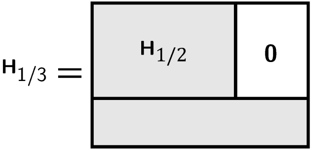


Punctured bits

[0 1 0] → Encoder → [0 1 0 0 1 1 0 1] → Puncturing → [0 1 0 0 X 1 X 1]

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



Motivations

- One of the challenging issues in optical satellite systems is the unreliable downlink channel.
  $\Longrightarrow$ **IR-HARQ** may offer better performance compared to ARQ and ECC for the desired system.
- Convolutional code and Reed-Solomon codes applied in the current design may not be efficient.
  $\Longrightarrow$ **LDPC code**, which has not been considered in the literature, is a potential solution for the design of IR-HARQ in such systems.
- To support the IR-HARQ, a proper design of the RC-LDPC code family is necessary.
  $\Longrightarrow$ **The RC-LDPC code family derived by code extension** is a more suitable approach compared to the one by the puncturing method.

➡ The IR-HARQ-based RC-LDPC code extension is a promising candidate for optical satellite systems.

Goals of the Study

1. We consider a design of the IR-HARQ-based LDPC code extension for optical satellite-aided IoV systems.
2. We study the performance of the design in terms of goodput and energy efficiency.
3. From the obtained results, we discuss the selection of a proper transmitted power

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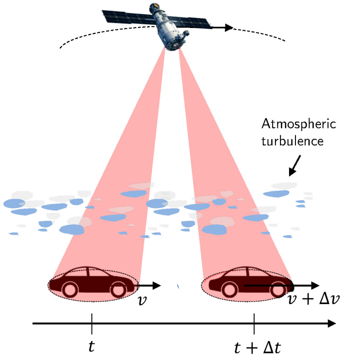
System Model



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

FSO Channel Model:

- Turbulence Fading
- Turbulence Attenuation
- Pointing error

Pointing Error Model:

- The vibration of the satellite
- The sudden change in vehicle's velocity over a short period of time

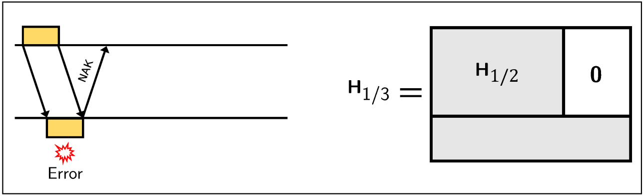
Considered Link-layer Solution: IR-HARQ based on RC-LDPC Code Extension

IR-HARQ based on RC-LDPC Code Extension

Operation Description

- RC-LDPC code family includes N_r code rates: $C_1 > C_2 > \ldots > C_{N_\mathsf{r}}$
- N_r is also the number of operated rounds of the IR-HARQ
- First round is the transmission of an LDPC-coded frame of rate C_1
- Subsequent round is the transmission of a frame with only redundancy
- This redundancy is combined with the received frame(s) to form a new frame of rate $C_2 > \ldots > C_{N_\mathsf{r}}$

Example: A systematic RC-LDPC code family $(1, 1/2, 1/3)$



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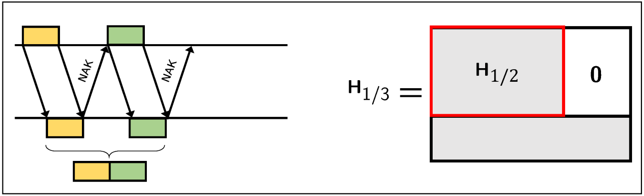

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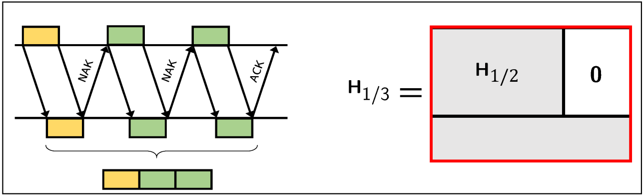
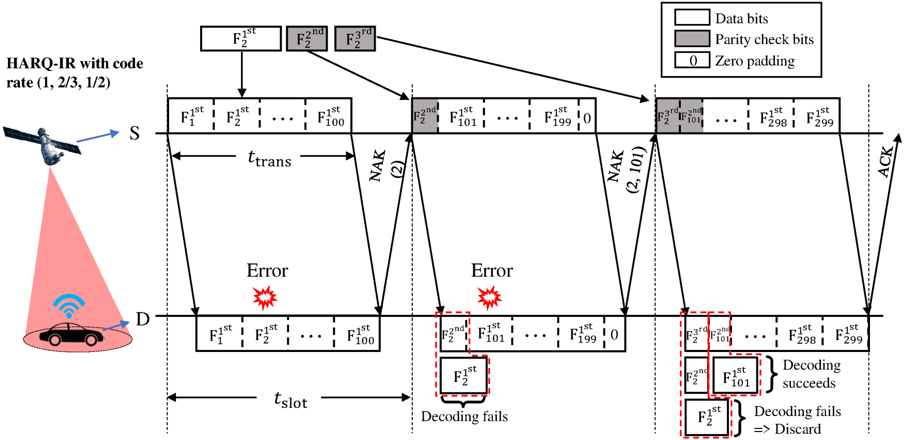


An Example of Data Transmission in the Considered System



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System Parameters

Table: System Parameters

Name	Symbol	Value
LEO Satellite Parameters		
LEO satellite altitude	H_s	500 km
Zenith angle	ξ	30°
Divergence half-angle	θ	20 μrad
Bit rate	R_b	1 Gbps
Burst duration	t_burst	6 ms
Optical wavelength	λ	1550 nm
Jitter angle	θ_jt	2 μrad
Vehicle Parameters		
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
Standard deviation of the velocity variation	σ_v	4 m/s
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$^{-2/3}$

Performance Evaluation Metrics

Goodput: The successfully transmitted data bits per second

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

Energy Efficiency: The successfully transmitted data bits per joule

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

Goodput Comparison among Link-layer Solutions

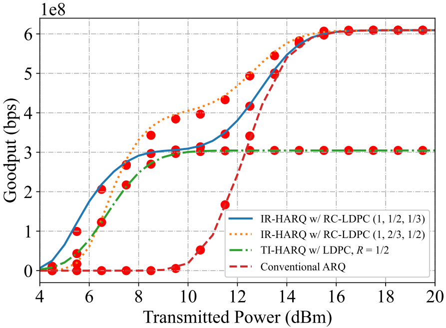

Figure: Goodput versus transmitted powers for different retransmission-based schemes.

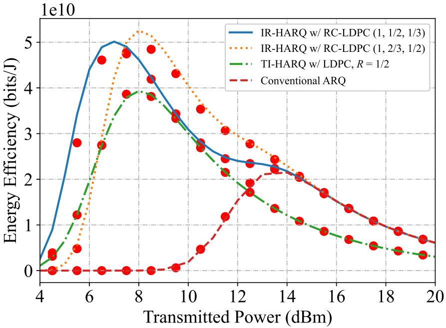

Figure: Energy efficiency versus transmitted powers for different retransmission-based schemes.

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

Goodput Performance over A Satellite Pass Duration

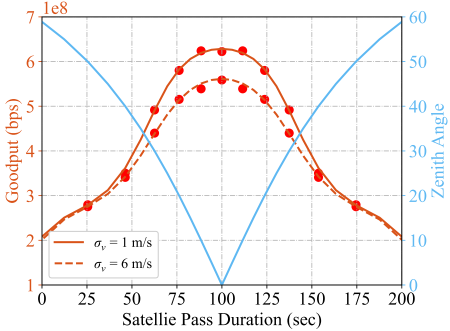

Figure: Goodput performance during a satellite pass duration for different values of velocity variation. The transmitted power is 13 dBm.

- **Satellite pass duration:** the period that the satellite may be available for line-of-sight communication.
- The goodput performance changes accordingly with the change of zenith angle.
- The impact of pointing errors is strongest when the beam footprint is smallest, or $\xi = 0°$.

Goodput Performance over A Satellite Pass Duration (cont.)

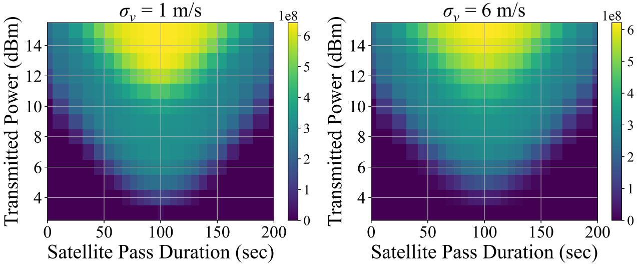

Figure: Goodput performance during a satellite pass duration with different values of transmitted power.

- We can determine the transmitted power to (1) maximize energy efficiency while (2) maintaining a targeted value of goodput during a (3) predefined zenith angle value.
- For example, when $\sigma_v = 6$ m/s, the transmitted power should be selected as 13 dBm to retain the targeted goodput of 400 Mb/s for the zenith angle $\xi < 40°$.

Conclusion

1. Consider an IR-HARQ-based LDPC code extension design to address the unreliable transmission issue of optical satellite-assisted vehicular networks.
2. Highlight the effectiveness of the IR-HARQ compared to TI-HARQ and ARQ in terms of goodput energy efficiency
3. Discuss the proper selection of transmitted power for the considered system.