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

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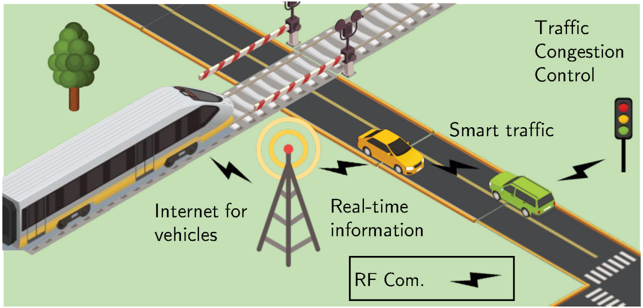
Outline

Internet of Vehicles (IoVs)

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

Limitations:

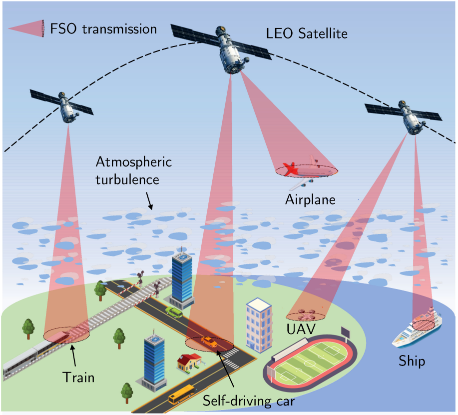
1. Radio-frequency (RF) band $\Longrightarrow$ Restricted data rate
2. Terrestrial infrastructure $\Longrightarrow$ Limited coverage



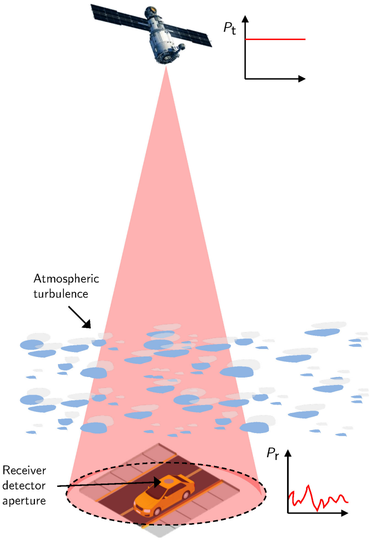
Optical Satellite Communication

1. **Data rate limitations:** Free-space Optical (FSO) Commun.
   - Infrared wavelength (700-1600 nm)
   - Higher data rate ($\sim$ Gbps)

2. **Coverage limitation:** Low-earth orbits (LEO) Satellite Constellation Network
   - Altitude: $\leq$ 2000km
   - Low latency, low cost
   - Global coverage



Optical LEO satellite is a potential technology to enable more applications for the IoVs



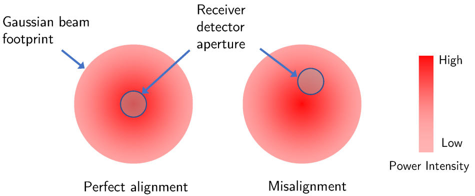
1. **Atmospheric Turbulence**

Cause: Inhomogeneity in temperature and pressure along the propagation path
Effect: Fluctuated received signal

2. **Pointing Misalignment**

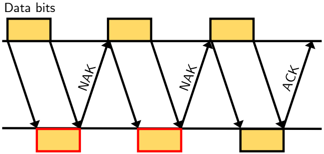
Cause: Misalignment between the beam footprint and the receiver detector
Effect: Lower received power

⇒ Transmitted data has a high bit-error rate (BER)

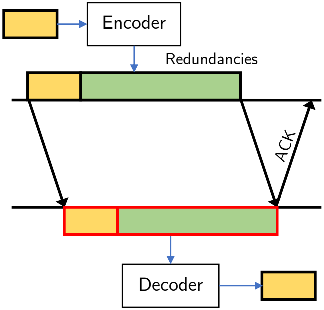


Possible solutions: **Automatic Repeat Request (ARQ)**, **Error Correction Code (ECC)**, and **Hybrid ARQ (HARQ)**

1. **Automatic Repeat Request (ARQ):** Retransmit erroneous frames



2. **Error Correction Code (ECC):** Add redundancy to correct a number of errors

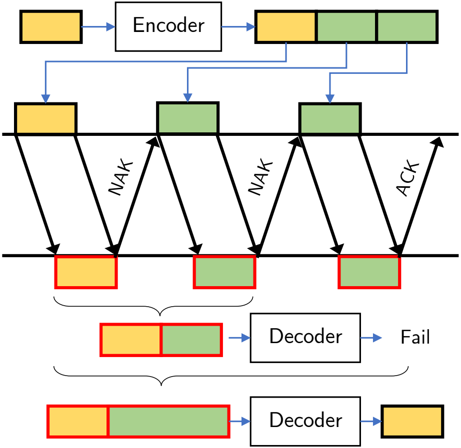


Possible Solutions: Reliable Trans. Protocols (Cont.)

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

Incremental Redundancy (IR)-HARQ:

1. Transmits redundancy when data is erroneous
2. Uses transmitted redundancies to decode



➡ IR-HARQ is the most efficient protocol among other protocols for the considered system

Literature Review

Major Studies of HARQ designs for optical satellite systems

[1] S. Parthasarathy, A. Kirstaedter, and D. Giggenbach, “Performance analysis of adaptive hybrid ARQ for inter-HAP free-space optical fading channel with delayed channel state information,” in *Proc. IEEE Photon. Netw.*, 2016, pp. 1–7
[2] H. D. Nguyen, H. D. Le, C. T. Nguyen, and A. T. Pham, “Throughput and delay performance of cooperative HARQ in satellite-HAP vehicle FSO systems,” in *Proc. IEEE Veh. Technol. Conf.*, 2021, pp. 1–6.
[3] H. D. Le and A. T. Pham, “On the design of FSO-based satellite systems using incremental redundancy hybrid ARQ protocols with rate adaptation,” *IEEE Trans. Veh. Technol.*, vol. 71, no. 1, pp. 463–477, Jan. 2022.

ECCs of current designs: **convolutional code** and **Reed-Solomon code**.
However, these ECCs may not be efficient in high data rate optical systems, where **long blocklength frames** are preferable.

- **Convolutional Code:** Performance can not compete with block codes
- **Reed-Solomon Code:** High complexity of encoding and decoding

⇒ It is necessary to have a design of proper ECC

Low-density Parity Check (LDPC) Code

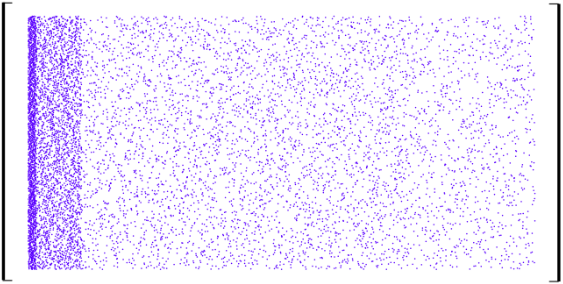
Low-density Parity Check (LDPC) code

- Linear block codes
- Sparse parity check matrix

Advantages over long blocklength frames

- Capacity-approaching performance
- Low decoding complexity

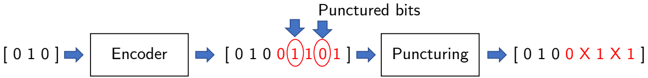
$\mathbf{H} =$



Rate-compatible (RC)-LDPC Code Family

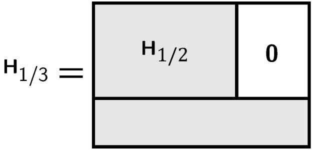
RC-LDPC code family: A set of LDPC code rates that can be decoded by the same parity check matrix

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



Motivations & Contributions

Motivations

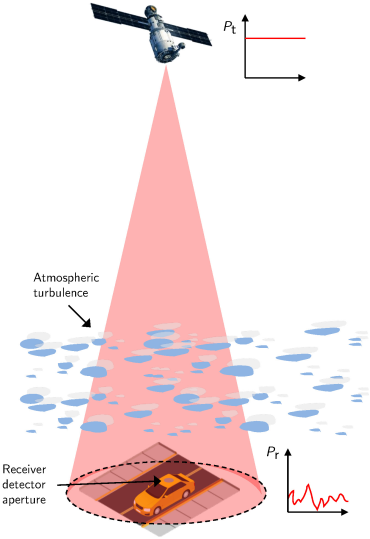
- One of the challenging issues in optical satellite-aided IoVs systems is the unreliable downlink channel.
  $\Longrightarrow$ **IR-HARQ** offers outstanding performance over time-varying channels compared to other reliable protocols.
- Convolutional and Reed-Solomon codes applied in the current design 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 puncturing.

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

Contributions: We study the performance of IR-HARQ-based LDPC code extension for the optical channel from an LEO satellite to a vehicular network

Outline

System Model



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

FSO Channel Model:

- Turbulence Fading
- Turbulence Attenuation
- Beam Spreading Loss

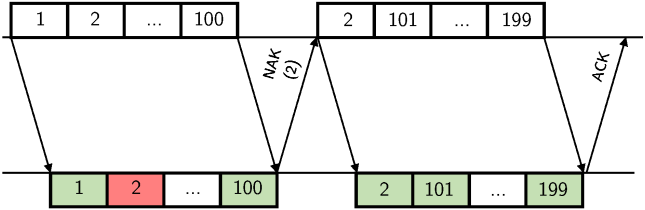
Considered Reliable Protocol: IR-HARQ

- Sliding window ARQ
- RC-LDPC code extension

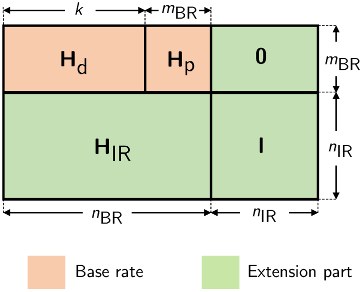
Sliding window ARQ

Sliding window ARQ: Multiple frames are transmitted at a time
Considered system: High data rate ($\sim$ Gbps), long channel coherent time ($\sim$ ms)

We design the window size of the sliding window ARQ to be **shorter** than the channel coherent time



RC-LDPC: Structural Diagram of Parity Check Matrix



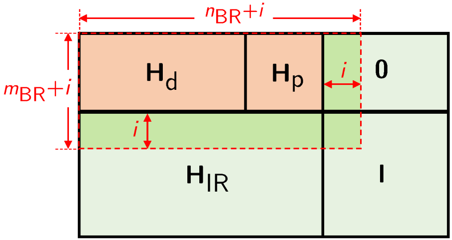
Base rate:

- $\mathbf{H}_\mathrm{d}$: matrix corresp. to data bits
- $\mathbf{H}_\mathrm{p}$: matrix corresp. to parity bits

Extension part:

- $\mathbf{H}_\mathrm{IR}$: matrix corresp. to incremental rates
- $\mathbf{I}$: indentity matrix
- $\mathbf{0}$: zero matrix

RC-LDPC: Code Rates of the Family



The check matrix of an arbitrary rate $\frac{k}{n_{BR}+i}$ is obtained by **extending the base matrix by i numbers of rows and columns**.

The possible code rates of the family:

$$\left[\frac{k}{n_{BR}}, \frac{k}{n_{BR}+1}, \ldots, \frac{k}{n_{BR}+n_{IR}}\right]$$

RC-LDPC: Encoding Method

Good encoding method: Systematic and low complexity.

Systematic:

- Generator matrix for the base rate

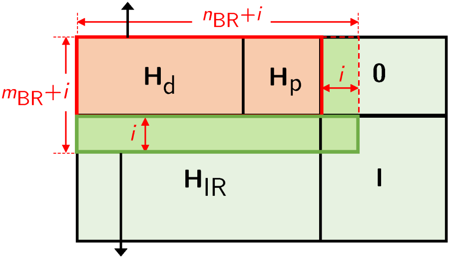
$$\mathbf{G}_{\mathrm{BR}} = \begin{bmatrix} \mathbf{I} & \mathbf{H}_{\mathrm{d}}^{\mathrm{T}} \mathbf{H}_{\mathrm{p}}^{-\mathrm{T}} \end{bmatrix}$$

- Generator matrix for an arbitrary rate

$$\mathbf{G}_{\mathrm{IR}}^{(i)} = \mathbf{G}_{\mathrm{BR}} \begin{bmatrix} \mathbf{I} & \left(\mathbf{H}_{\mathrm{IR}}^{(i)}\right)^{\mathrm{T}} \end{bmatrix}$$

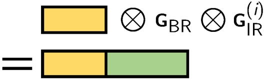
Low complexity: Because all the matrices are sparse $\Longrightarrow$ Low complexity encoding

$$\mathbf{H}_{\mathrm{BR}} = [\mathbf{H}_{\mathrm{d}} \;\; \mathbf{H}_{\mathrm{p}}] \Leftrightarrow \mathbf{G}_{\mathrm{BR}} = \left[\mathbf{I} \;\; \mathbf{H}_{\mathrm{d}}^{\mathrm{T}} \mathbf{H}_{\mathrm{p}}^{-\mathrm{T}}\right]$$



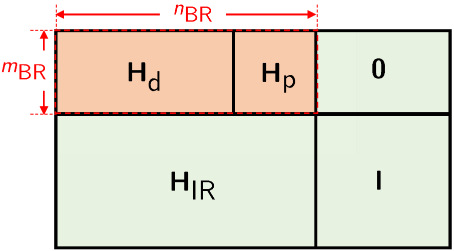
$$\left[\mathbf{H}_{\mathrm{IR}}^{(i)} \;\; \mathbf{I}\right] \Leftrightarrow \mathbf{G}_{\mathrm{IR}}^{(i)} = \left[\mathbf{I} \;\; \left(\mathbf{H}_{\mathrm{IR}}^{(i)}\right)^{\mathrm{T}}\right]$$

Example:

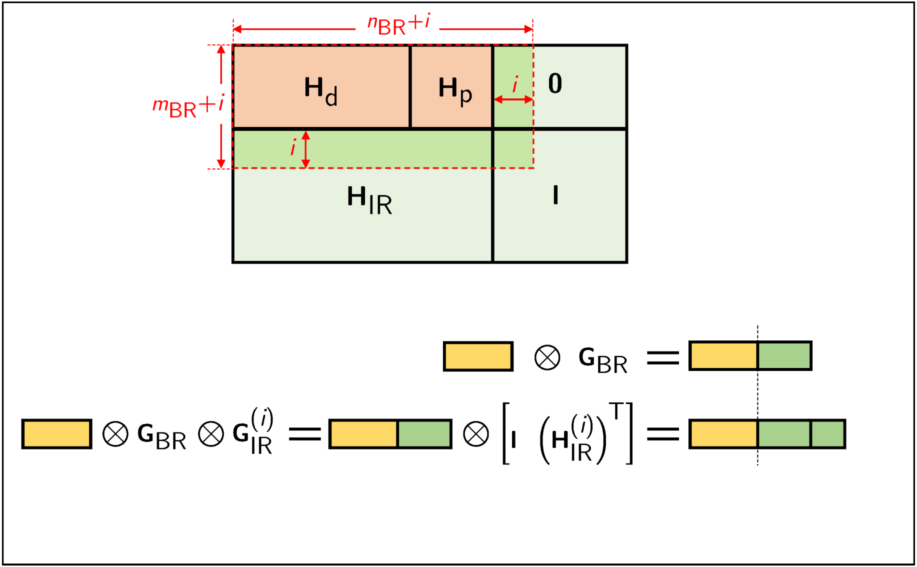


$$\text{Code rate} = \frac{k}{n_{\mathrm{BR}}+i}$$

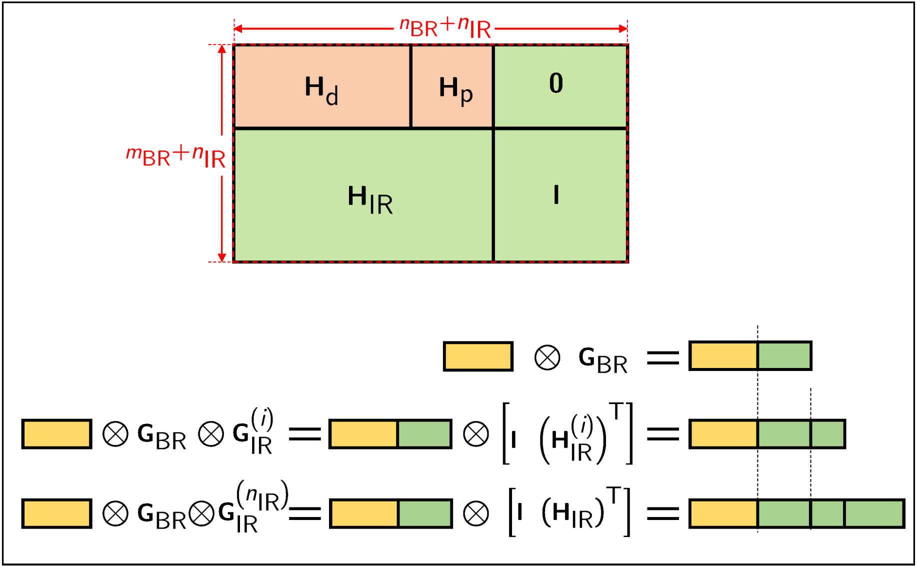
RC-LDPC: An Example of Encoding (1)



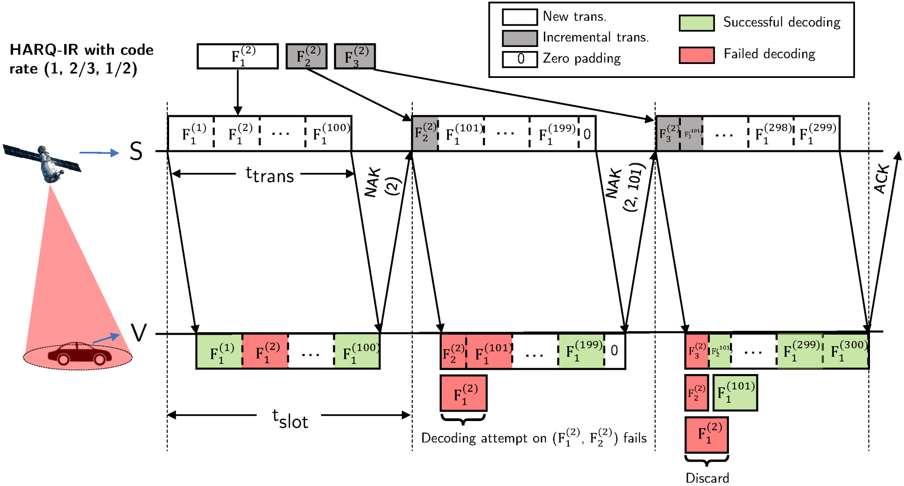
RC-LDPC: An Example of Encoding (2)



RC-LDPC: An Example of Encoding (3)



An Example of Data Transmission



Outline

I. Introduction

II. System Description

III. Results & Discussions

IV. Extension Directions

System Parameters

Name	Symbol	Value
LEO Satellite Parameters		
LEO satellite altitude	H_{s}	600 km
Zenith angle	ξ	$60°$
Divergence half-angle	θ	10 μrad
Bit rate	R_{b}	1 Gbps
Number of bits per burst	N_{burst}	1.6 Mbits
Optical wavelength	λ	1550 nm
Vehicle Parameters		
Vehicle altitude	H_{v}	1.5 m
Aperture radius	r_{a}	5 cm
Radical displacement	ρ	0 m
Noise spectral density	σ_{n}^2	10^{-14} 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$^{-2/3}$
Visibility	V	20 km

Evaluation Metrics

Goodput: The successfully transmitted data bits per burst

$$\text{Goodput} = \frac{\#\text{ of successfully transmitted data bits per burst}}{\#\text{ of burst simulated}}$$

Energy Efficiency: The successfully transmitted data bits per joule

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

Goodput vs. Signal-to-Noise Ratio (SNR)

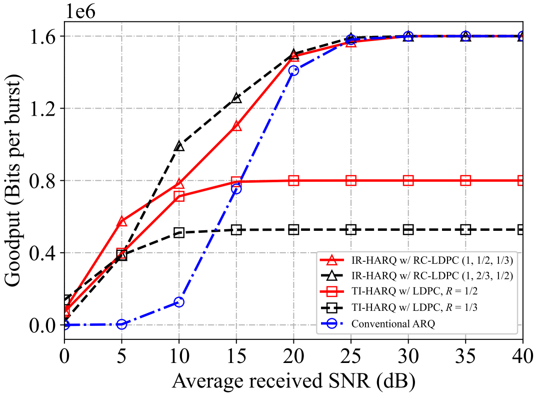


Figure: Goodput versus average received SNR for different retransmission-based schemes.

Goodput vs. Radial Displacement

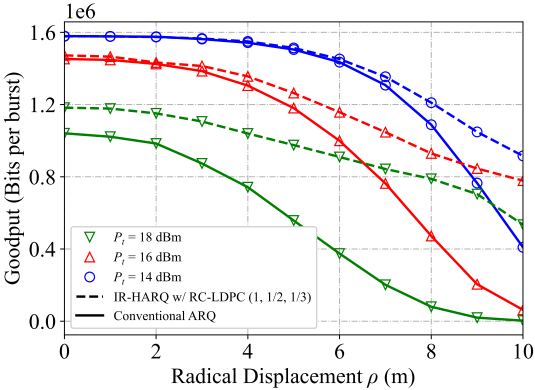


Figure: Goodput versus radical displacements for different transmitted power values.

Energy Efficiency vs. Transmitted Power

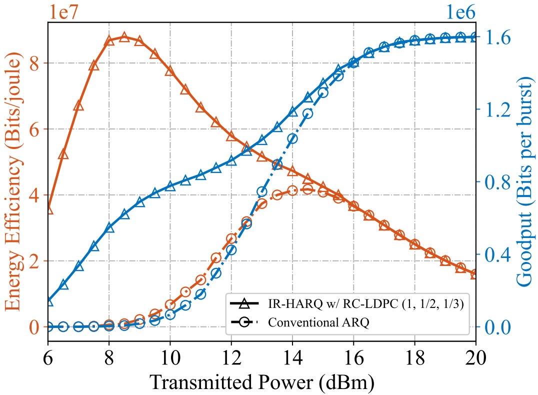
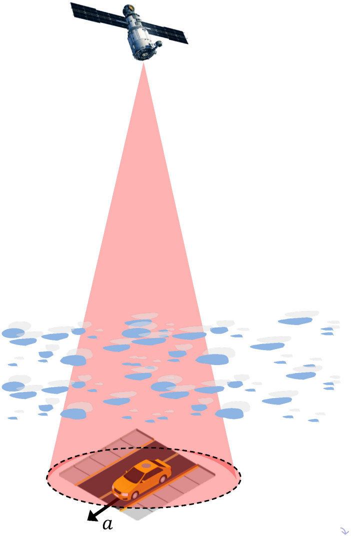


Figure: Energy efficiency and goodput versus transmitted power for LDPC-based IR-HARQ and conventional ARQ.

Outline

Directions for the Extension: Pointing Error Model

1. Consider a pointing error model for the FSO channel model
   - Conf. paper: Assume perfect tracking
   - Ext. paper: Pointing error model between the satellite and the moving vehicle



Directions for the Extension: Theoretical Analysis

2. Analyze the theoretical performance of the system

$f_h(h)$: PDF of the composite channel

⇓

$\overline{\text{FLR}}_i$: average frame loss rate at i-th transmission

⇓

Markovian burst transmission model

⇓

- Goodput
- Energy efficiency
- Average frame delay

Considered in Conf. paper

Conclusion

1. We consider an IR-HARQ-based LDPC code extension design to address the unreliable transmission issue of optical satellite-assisted vehicular networks.
2. The system performance is evaluated in terms of goodput and energy efficiency.
3. From the simulation results, it can be seen that the IR-HARQ-based LDPC code extension outperforms the conventional ARQ.