LDPC-based HARQ for Optical Satellite-Assisted Internet of Vehicles

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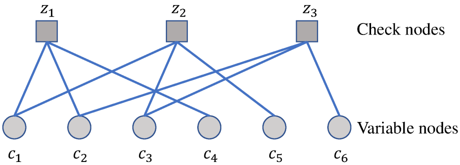
Outline

Low-density Parity-check Codes

- Low-density parity-check (LDPC) codes are linear block codes with a **sparse parity check matrix**
  - A matrix is said to be **sparse** if *more than half of its elements are zero*
  - Parity check matrix can be graphically presented by a Tanner graph
- **History of LDPC codes**
  - LDPC codes were first introduced by Gallager in 1962
  - However, they were forgotten for a long time until MacKay rediscovered them in 1995
- **Applications**: 5G New Radio (NR), WiMAX (IEEE 802.16), Wifi 6 (IEEE 802.11ax)

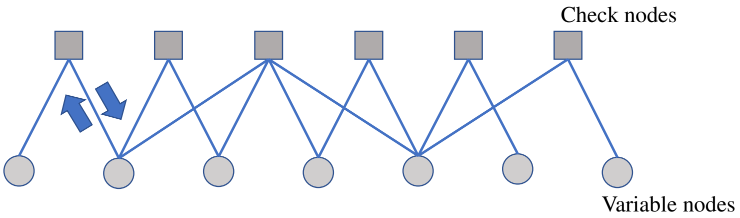
$$\mathbf{H} = \begin{pmatrix} 1 & 1 & 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 \end{pmatrix} \begin{matrix} z_1 \\ z_2 \\ z_3 \end{matrix}$$

$$\quad c_1 \quad c_2 \quad c_3 \quad c_4 \quad c_5 \quad c_6$$



Iterative Decoding Algorithms

- **Iterative decoding algorithms** are decoding algorithms for linear block codes
  - The basic idea of iterative decoding algorithms is the *information update* between VNs and CNs
  - The erroneous bits are then gradually corrected



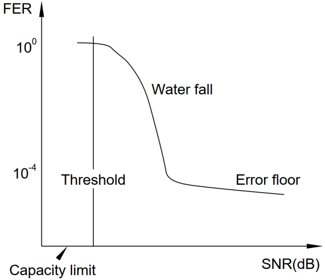
- Thanks to the spareness of the parity check matrix, the LDPC codes can be decoded with **linear-time complexity** by iterative decoding algorithms

⇒ LDPC codes can implement long codewords with practical decoding time

Decoding Threshold

- The performance of an LDPC code can be evaluated by the **decoding threshold**

- **Decoding threshold** is the *minimum value of SNR* that long codewords can be decoded successfully by iterative decoding algorithms



- To compare the performance of different code rates, we can compute *the distance between its decoding threshold and channel capacity*, or **gap to capacity**

Outline

Rate-Compatible LDPC Codes

- **Rate-compatible (RC) family** is a nested family of codes where *higher code rates are parts of lower code rates*
- Advantages of RC family code
  1. Allows coding across a range of rates using a common encoder/decoder infrastructure
  2. Allows the change of code rate to adapt the channel conditions
- For LDPC codes, RC family can be obtained by two common methods, i.e., **puncturing** and **code extension**

Puncturing

- **Puncturing** is the process in which we remove columns from a parity check matrix of low-rate code to obtain that of higher-rate codes
- **Iterative decoding algorithms** depend heavily on code structure while puncturing affects *the structure of optimized mother code rate*

$\Longrightarrow$ Obtained codes from puncturing may have poor performance for iterative decoding

- **For example:** Consider the punctured family of RC-LDPC codes with the base code rate of 1/2[1]

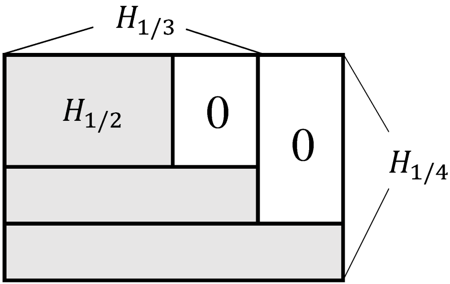
Code rate	Decoding threshold (dB)	Capacity threshold (dB)	Gap to capacity (dB)
1/2	0.357	0.188	**0.169**
3/5	1.2	0.683	**0.275**
4/5	2.9	2.088	**0.83**

The obtained code rates by puncturing tend to have a **wider gap** to capacity

[1] M. El-Khamy, J. Hou, and N. Bhushan, “Design of rate-compatible structured ldpc codes for hybrid arq applications,” *IEEE J. Sel. Areas. Commun.*, vol. 27, no. 6, pp. 965–973, Aug. 2009.

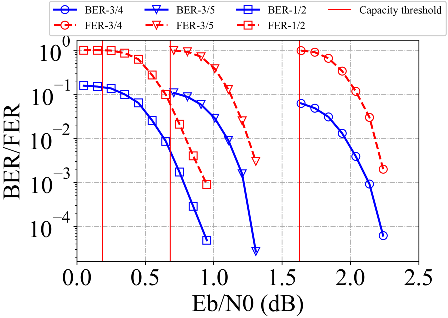
Code Extension

- **Code extension** is a method to construct RC-LDPC codes by extending the parity check matrix by *an equal number* of columns and rows
- *Lower-rate codes* are obtained by extending the parity check matrix of a base code rate



Code Extension: My Results

- The figure plots the BER/FER performance of different code rates by code extension with the base code of 3/4



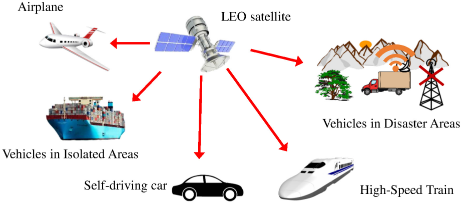
Code rate	Decoding threshold	Capacity threshold	Gap to capacity
3/4	1.706	1.628	**0.078**
3/5	0.785	0.682	**0.103**
1/2	0.278	0.188	**0.090**

⇒ The obtained code rates by code extension have **uniform gaps** to the capacity

Outline

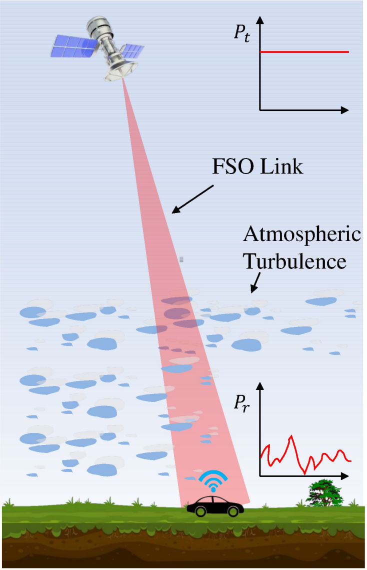
Optical Satellite-Assisted Internet of Vehicles (IoVs)

- **Internet of Vehicles (IoV)** is defined as the network of vehicles and related entities to connect and exchange data over the Internet
- **Applications**
  - Safety: emergency call, speed control, ...
  - Navigation: traffic congestion control, real-time information, parking helper, ...
  - Business: high-speed Internet for vehicles, infotainment, ...



- *To support the future applications of IoVs*, free-space optical (FSO)-based satellite is expected to be a **key technology**
  1. **Extremely high data rate** (Gbps or even Tbps) thanks to the *usage of infrared frequency bands (187-400 Thz)*
  2. **Global coverage area** with the *assistance of low-earth orbit (LEO) satellites*

Challenging Issues



- The FSO link is adversely affected when propagating through the atmosphere

1. **Atmospheric Attenuation**
   - Caused by molecular absorption and aerosol scattering
   - Happens mostly in the range below 20 km

   $\Longrightarrow$ Reduction in the received power
2. **Atmospheric Turbulence**
   - Caused by inhomogeneity in temperature and pressure along the propagation path

   $\Longrightarrow$ Fluctuation in the received signal

The channel of optical satellite systems is unreliable

Possible Solutions: Reliable Methods

- *To cope with unreliable channels*, reliable transmission protocols are implemented
  - Two common methods: **Automatic Repeat reQuest (ARQ)** and **Error Correction Code (ECC)**

1. **Automatic Repeat reQuest (ARQ)**: Retransmit erroneous frames
   - *In a time-varying channel*, increase the frequency of retransmissions when the channel is noisy

   $\Longrightarrow$ Increase the delay, *especially in satellite systems*
2. **Error Correction Code (ECC)**: Add redundancy to correct errors
   - Inefficient throughput due to the redundancy when the channel is less noisy
   - Lose the reliability once the frame is uncorrectable

- To mitigate the limitations of both protocols, **Hybrid ARQ (HARQ)** is proposed
  - Combination of ARQ and ECC
  - Data is encoded by ECC and used for (re)transmissions

Literature Reviews: HARQ in Optical Satellite Com.

- Survey of Major Studies of HARQ designs for optical satellite systems

Reference	Main Contributions
2016[2]	The performance of HARQ with adaptive rate **Reed-Solomon (RS)** code in an inter-HAPs' channel is evaluated under the effects of delayed CSI
2021[3]	A novel design of cooperative HARQ using the **puncturing RS** is proposed for FSO-based satellite-HAP-Vehicle system
2022[4]	The study considered the design of HARQ with sliding window and the **rate-compatible convolutional code (RCPC)** for FSO-based satellite-to-ground systems

⇒ The ECCs of current designs mainly focus on **Reed-Solomon** and **convolutional code**

[2] 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.*, VDE, 2016, pp. 1–7.

[3] H. D. Nguyen, H. D. Let, C. T. Nguyen, *et al.*, "Throughput and delay performance of cooperative harq in satellite-hap-vehicle fso systems," in *Proc. IEEE Veh. Technol. Conf. (VTC2021-Fall)*, IEEE, 2021, pp. 01–06.

[4] 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, 2021.

Motivations

- To cope with the time-varying channel of optical satellite communication, the usage of HARQ is necessary

$\Longrightarrow$ **HARQ Incremental Redundancy (IR)** is an efficient variant thanks to retransmissions of only redundancy parts when errors occur

- One of the most critical issues for HARQ designs in the context of IoVs is having a proper ECC satisfying low-complexity encoding and high efficiency

$\Longrightarrow$ **LDPC codes** are especially suitable for the design of HARQ in the context of IoVs

- When combining LDPC codes with HARQ-IR, a proper design of RC-LDPC is necessary

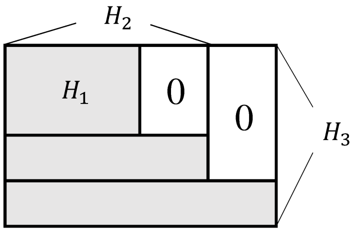
$\Longrightarrow$ The family of RC-LDPC codes by **code extension** shows good performance compared to the ones by puncturing

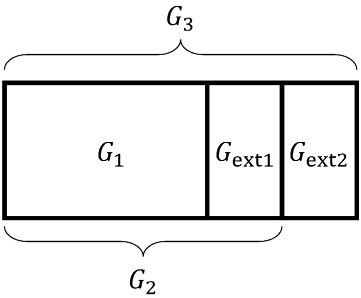
➡ **The combination of RC-LDPC by code extension and HARQ-IR is a promising candidate for the optical satellite-assisted IoVs**

Outline

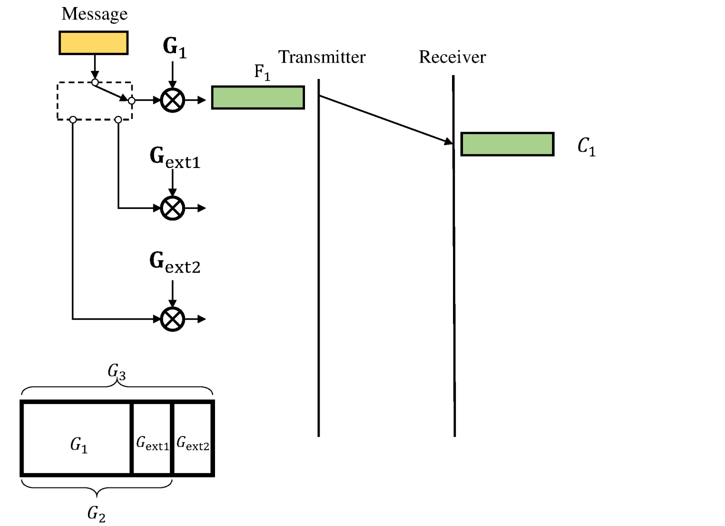
RC-LDPC by Code Extension

- The RC-LDPC codes are constructed from parity check matrices
- The generator matrices can be constructed in the nested form accordingly
- **Example:** Consider a family of RC-LDPC codes with three code rates $C_1 \geq C_2 \geq C_3$

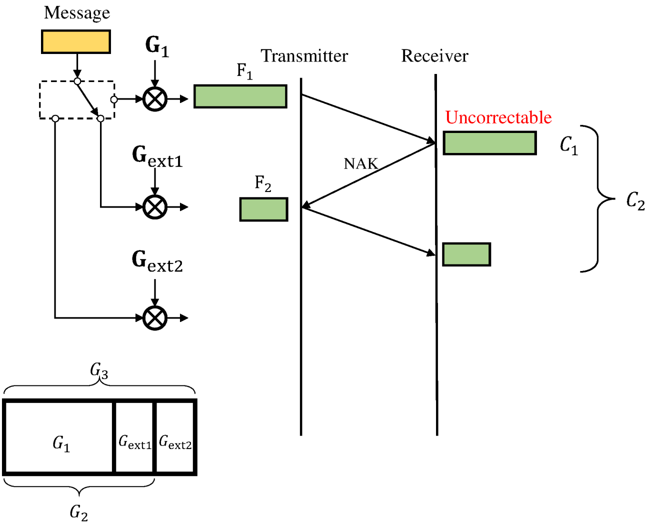




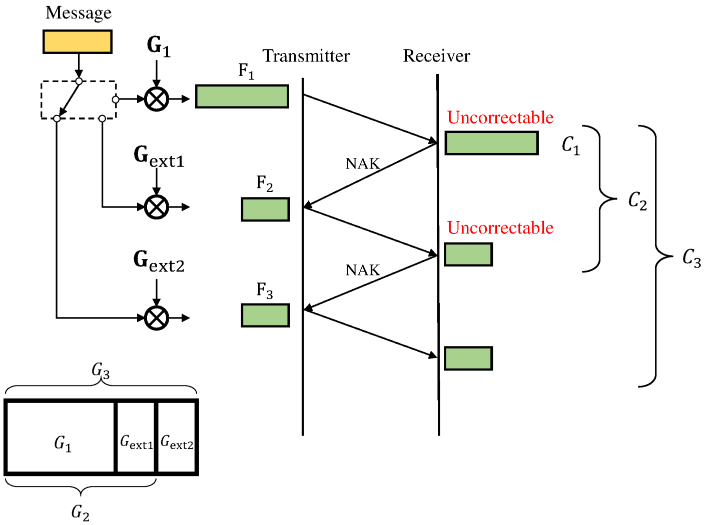
Example: HARQ-IR with RC-LDPC by Code Extension (1)



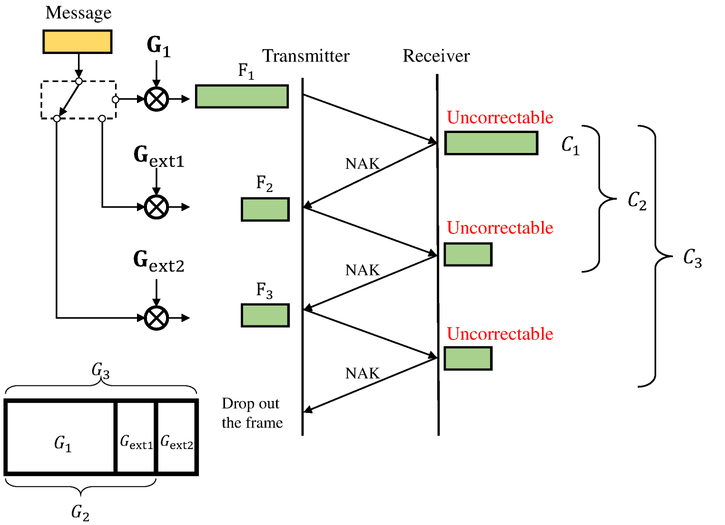
Example: HARQ-IR with RC-LDPC by Code Extension (2)



Example: HARQ-IR with RC-LDPC by Code Extension (3)



Example: HARQ-IR with RC-LDPC by Code Extension (4)



Proposal for Optical Satellite-Assisted IoVs

- **Example:** Consider an optical satellite system with HARQ-IR and burst transmission. The burst size $T_B = 100$ (frames) and HARQ persistent level is 3