A Survey on ARQ and Hybrid ARQ in Free-Space Optical (FSO) Systems

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Lab. Seminar
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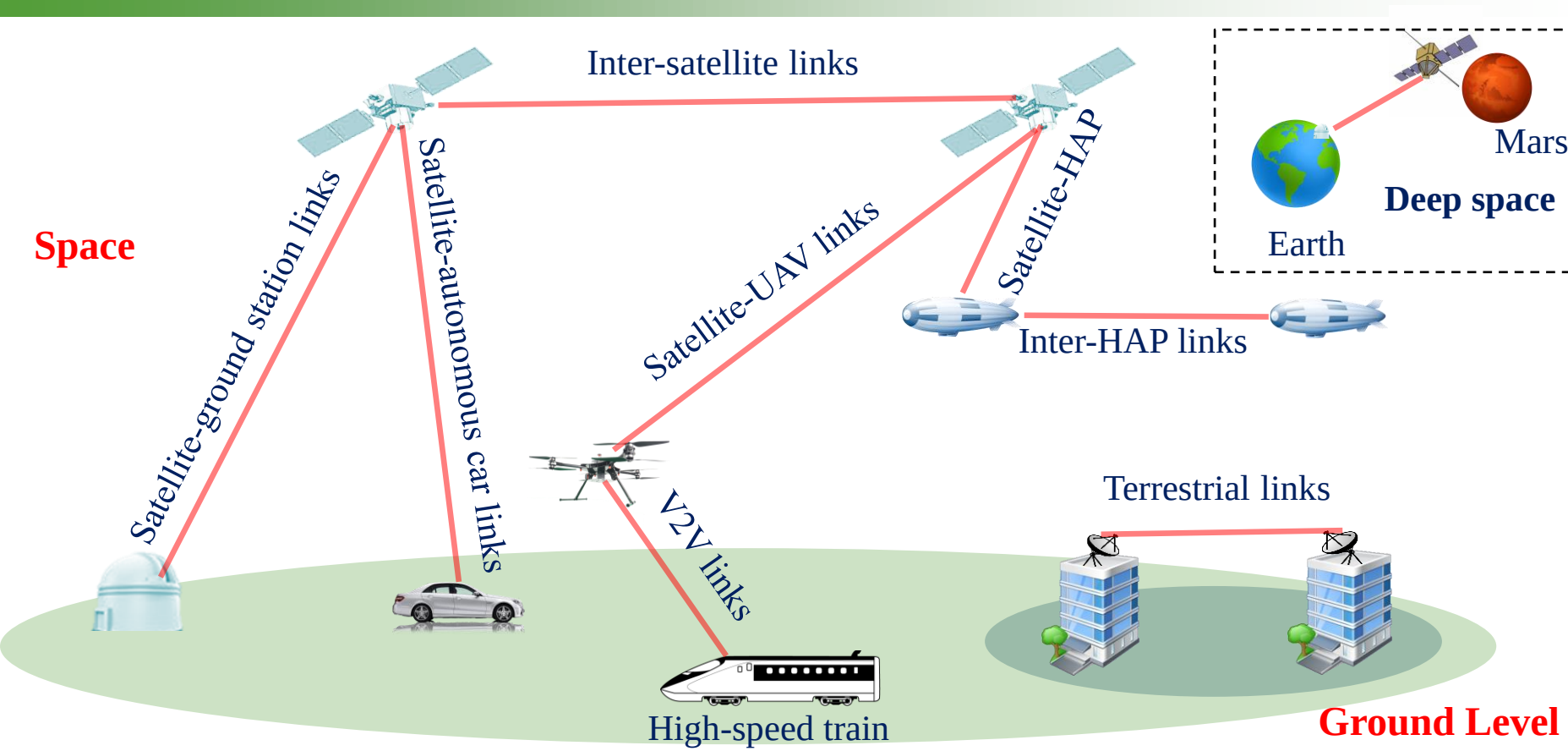
Outline of Presentation

- Introduction
- Part I: ARQ
  - Fundamental Principles
  - Literature Survey in FSO systems
- Part II: HARQ
  - How it works?
  - Existing state-of-art of HARQ in FSO systems

FSO Communications: Classification



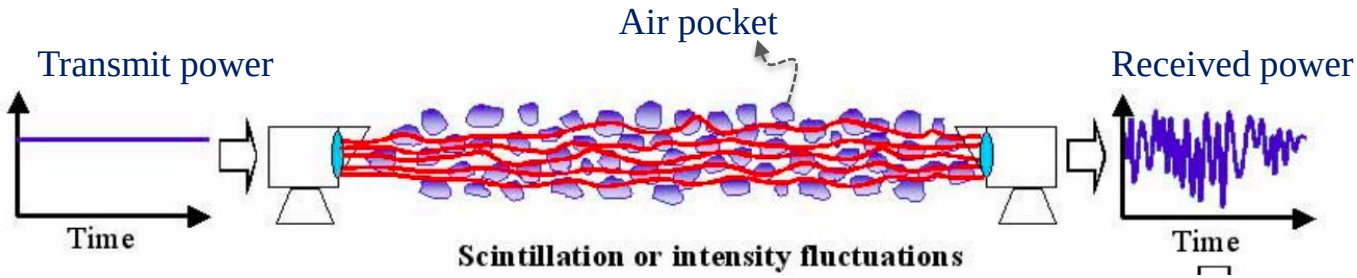
FSO (Outdoor Systems)

- **Terrestrial links** — e.g., building-to-building links
- **Space links** — e.g., Inter-satellite links

[1].2017. IEEE Com. Sur. Tuts.

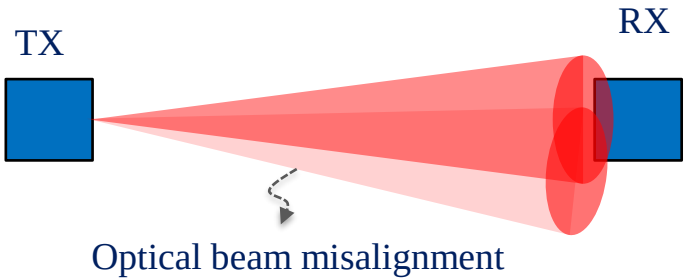
FSO Communications: Challenging Issues(1)

- Atmospheric Turbulence:
  - *A random phenomenon* due to the inhomogeneity in ***temperature*** and ***pressure*** of the atmosphere along the propagation path

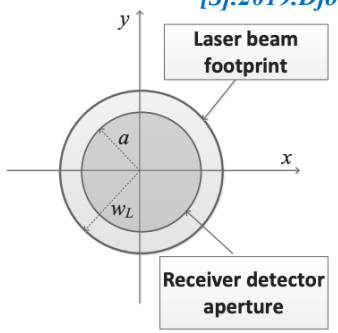


[2].2016. Kazaura's OSA Opt. Expr.

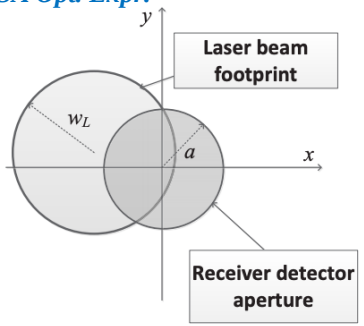
- Pointing Errors
  - *A random phenomenon* due to the ***beam misalignment*** between transceivers



[3].2019.Djordjevic's OSA Opt. Expr.



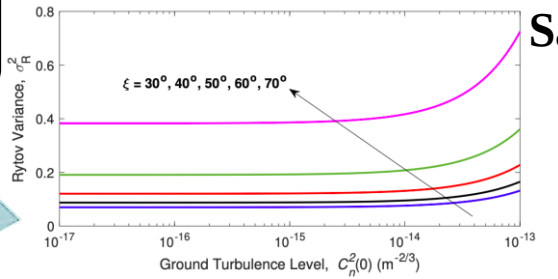
(a) without pointing error

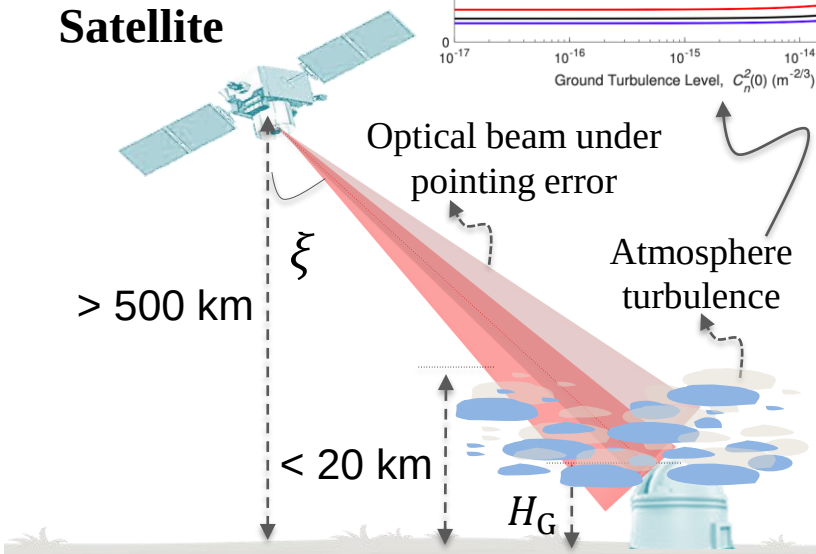


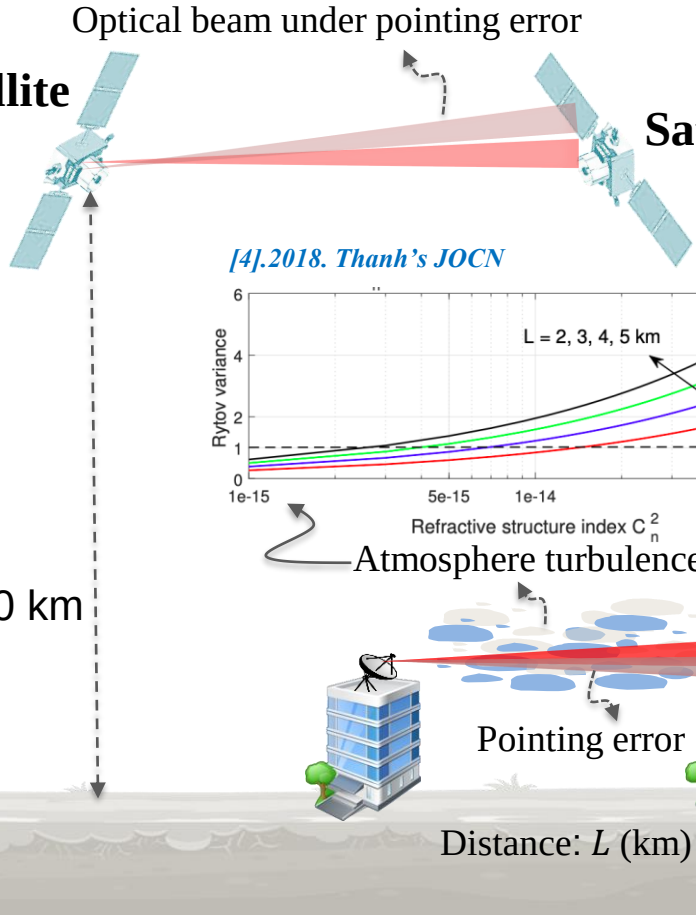
(b) with pointing error

FSO Communications: Challenging Issues(2)

- **Weak Tur.: Rytov < 1**
- **Moderate Tur.: Rytov ≈ 1**
- **Strong Tur.: Rytov > 1**



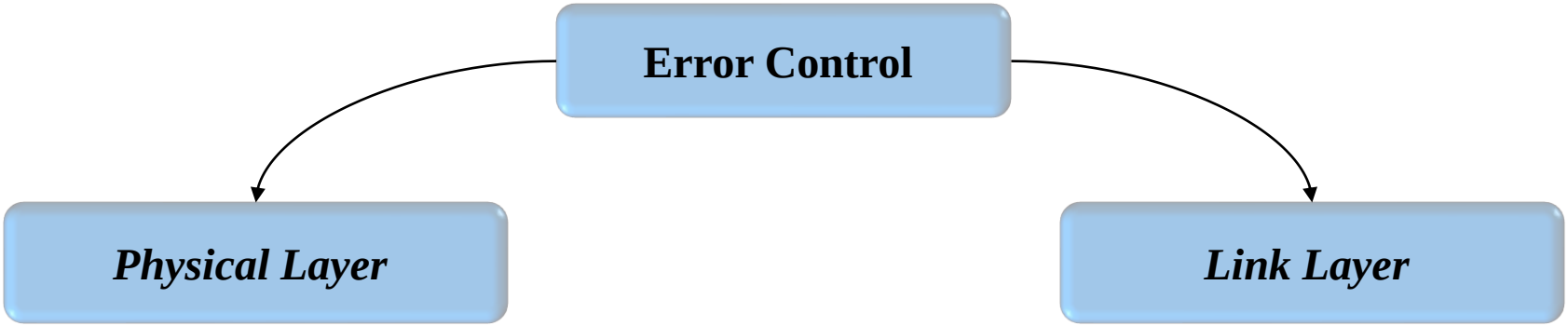




Different systems may experience different adverse issues!!!

Error Control Methods should be considered for reliable communications

Error Control Solutions



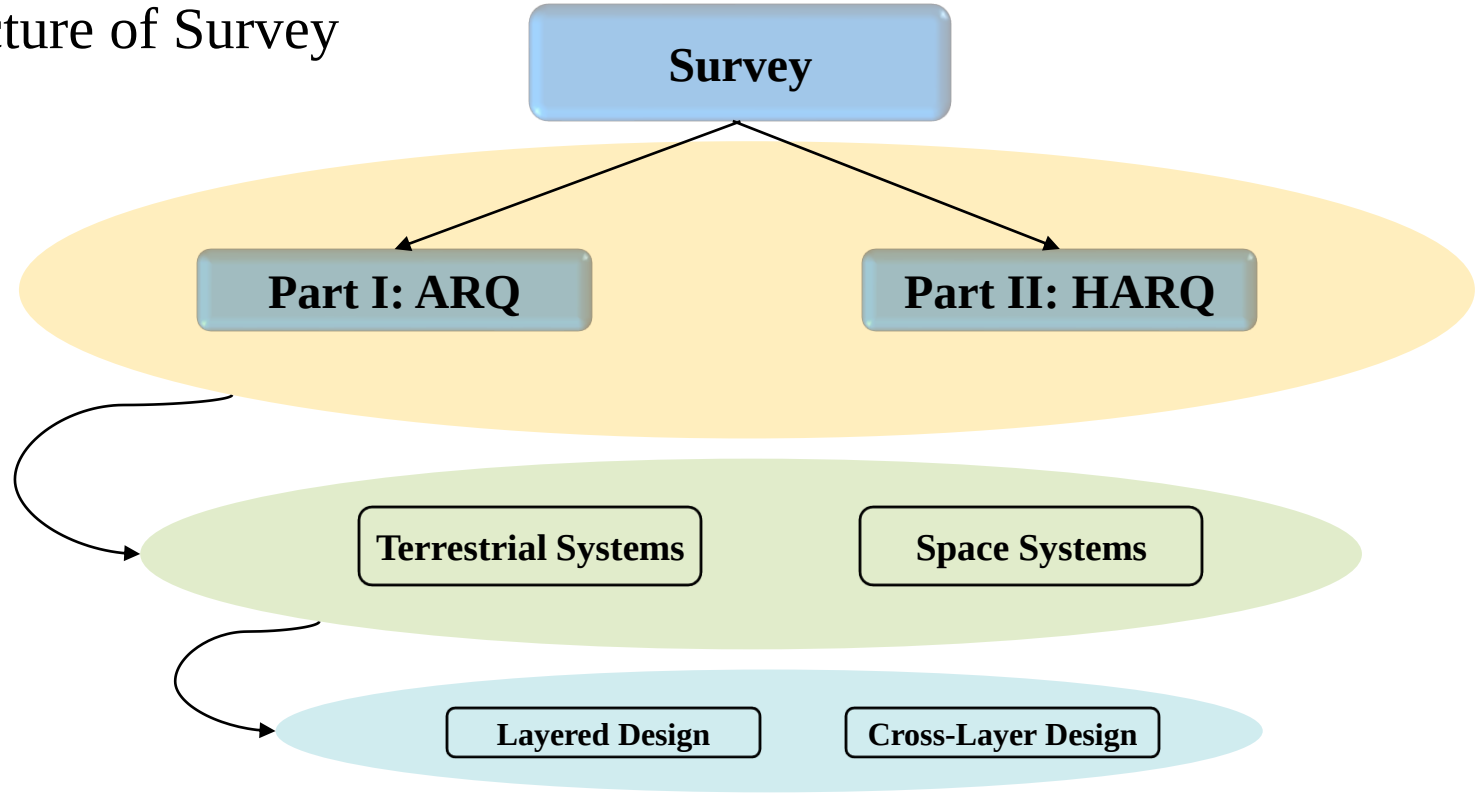
- Adaptive modulation and coding (AMC)
- Forward Error Correction Code (FEC)
- Adaptive Rate/Power Transmissions
- Multi-hop/Relay Communications
- Cooperative Communications, etc.,

- **Automatic repeat request (ARQ) + Error Detection Code (EDC)**
- Error Correction Codes (ECC)
- **Hybrid ARQ (HARQ)**, etc.

The main focus of this survey is about the Link-layer Error Control Methods including ARQ and HARQ protocols for FSO communications

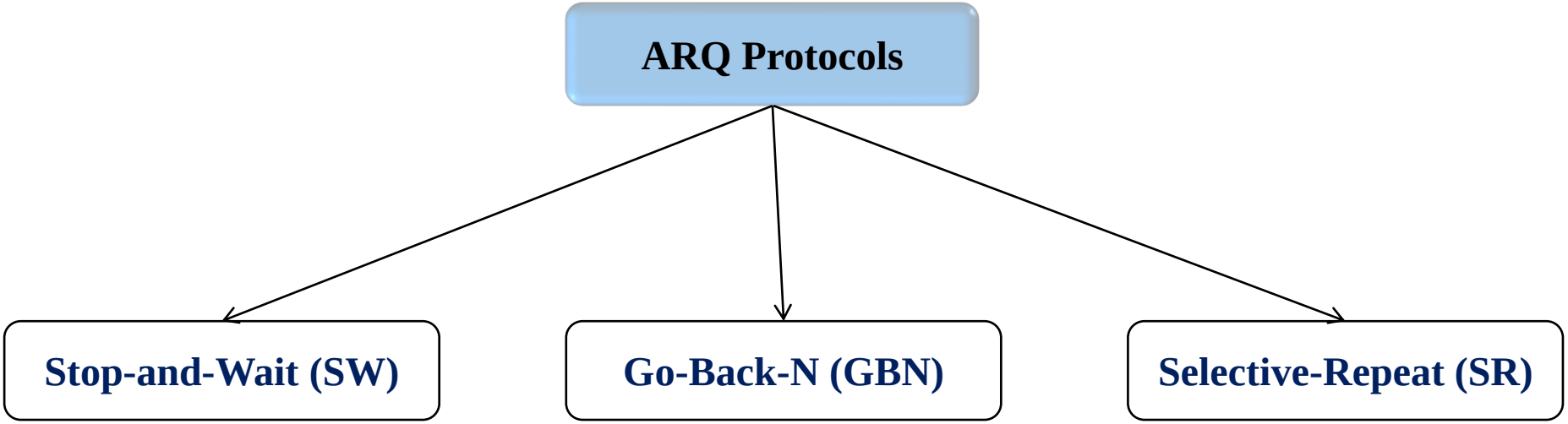
Survey: Methodology - Structure

- Design Methodologies
  - ***Layered Designs***: protocols of one layer are designed independently from ones of other layers.
  - ***Cross-Layer Designs***: allow the protocol design between layers by permitting one layer to access the data of another one to exchange the information and enable interaction.
- Structure of Survey

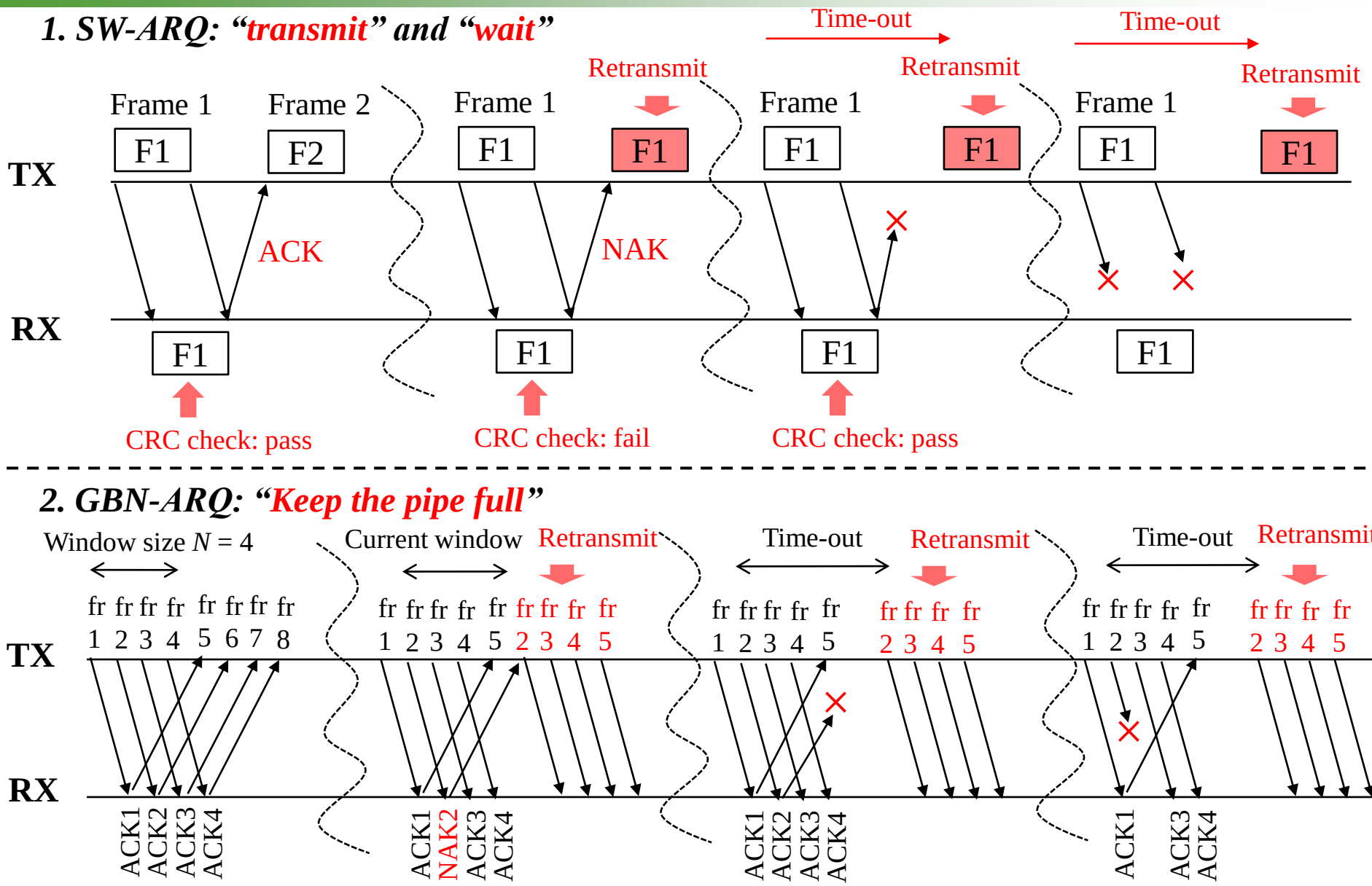


Part I: ARQ Aided FSO Communications

- ARQ operates at the link layer to *detect* and *retransmit* corrupted frames
  - ***Detect***: by using cyclic redundancy check (CRC), e.g., 32-bit CRC
  - ***Retransmit***: if a frame is failed with CRC
- Classification:

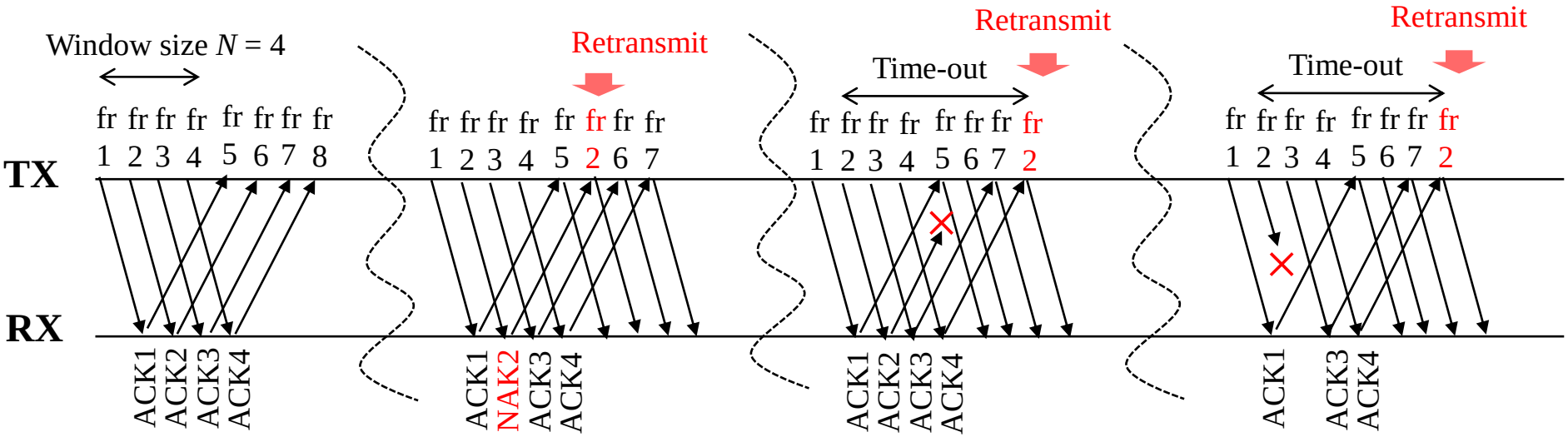


ARQ Protocols: How They Works? (1)

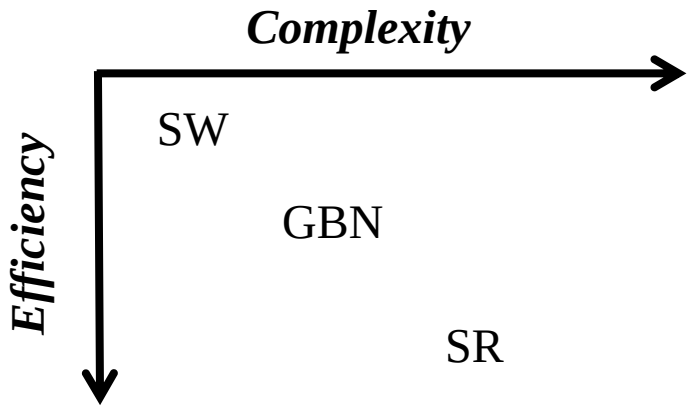


ARQ Protocols: How They Works? (2)

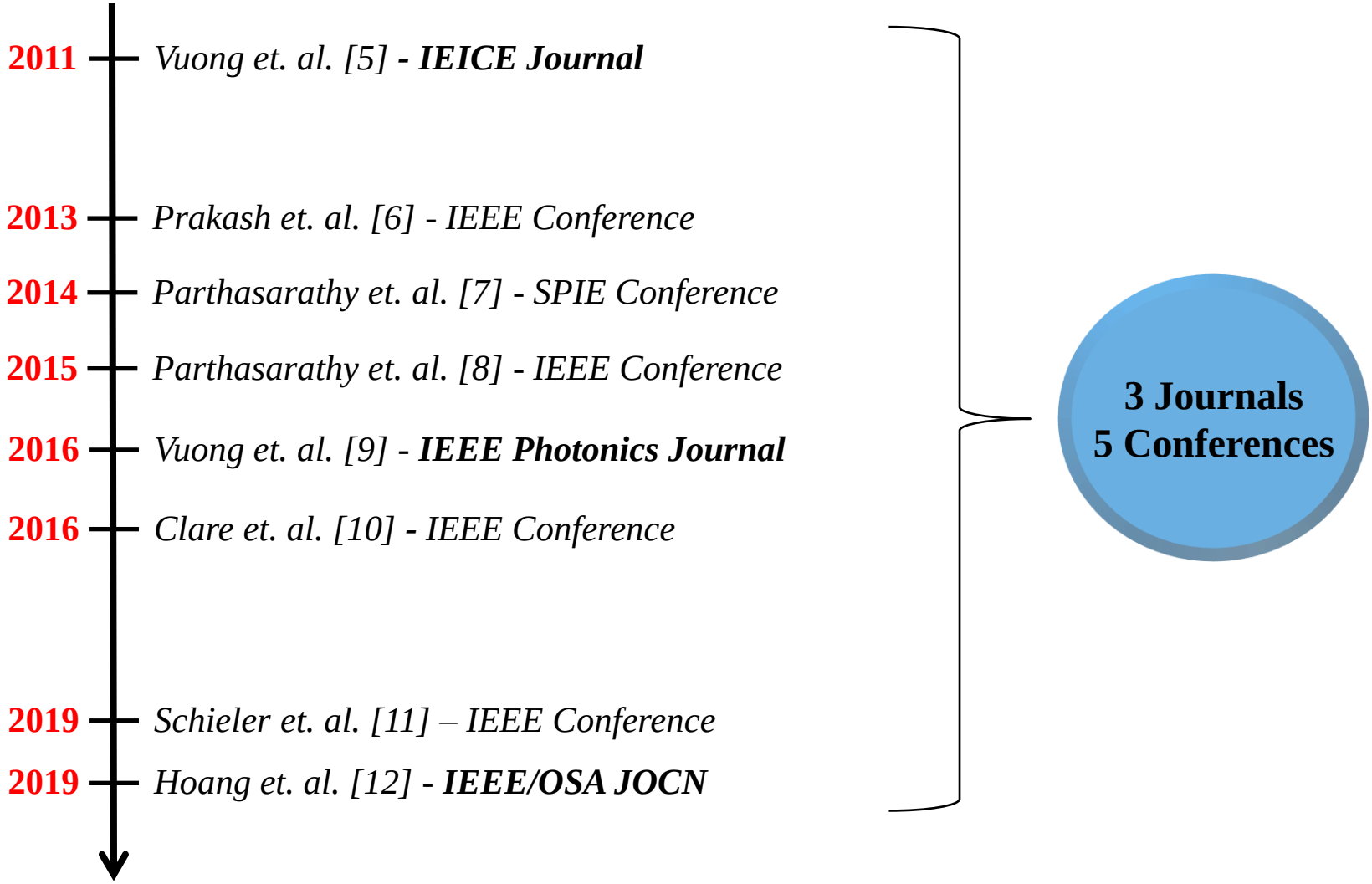
3. SR-ARQ: "keep the pipe full" and "retransmit selectively"



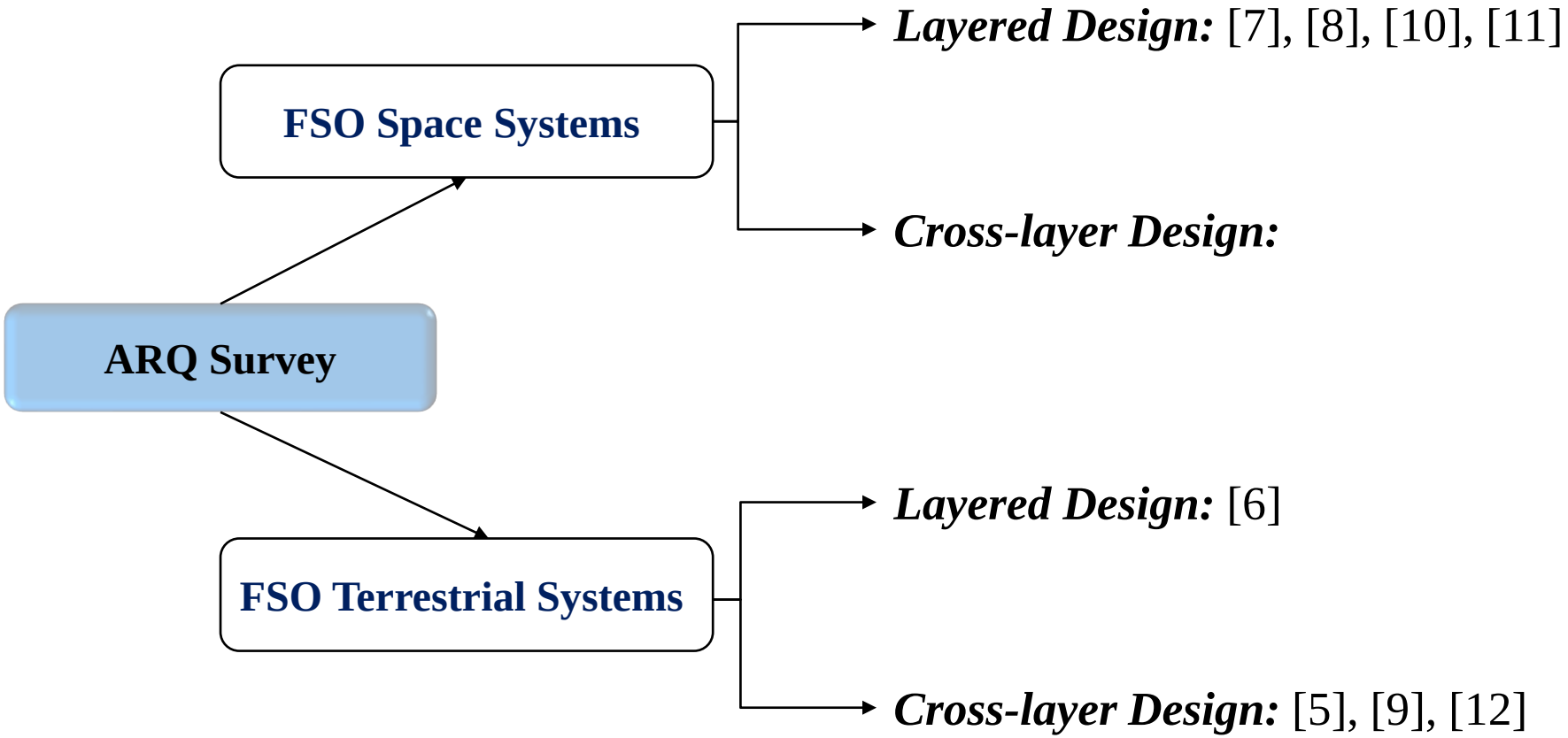
4. Comparison between protocols



Literature Survey of ARQ in FSO (1)

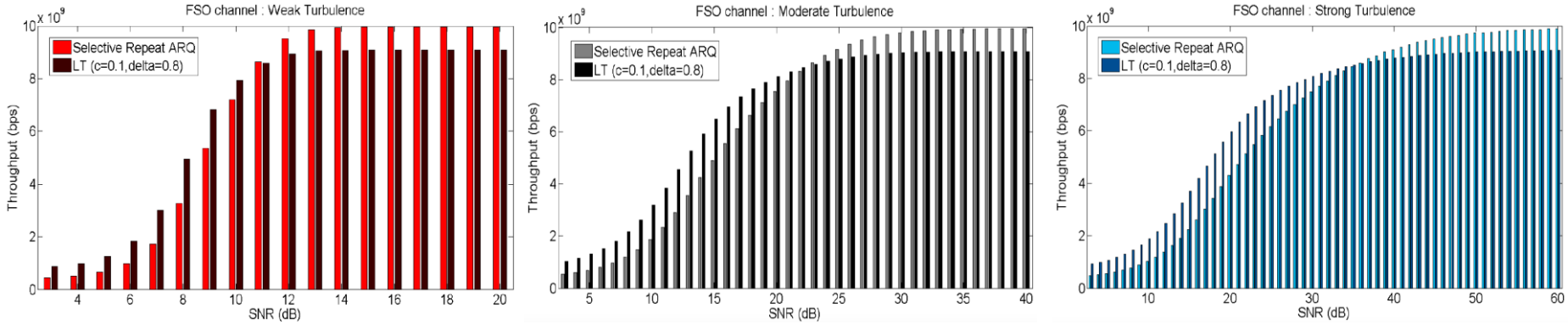


Literature Survey of ARQ in FSO (2)



ARQ in FSO Terrestrial (1): Layered Design

- *First*, ARQ and FEC are the most popular error control protocols. And one of the important questions: ARQ or FEC is suitable for FSO systems?
  - [6] was the first work that mentioned about this question



Comparison of Luby Transform (LT) Codes and selective-repeat ARQ

ARQ can work well in the less "noisy" environment (i.e., high received SNR and weak turbulence conditions)

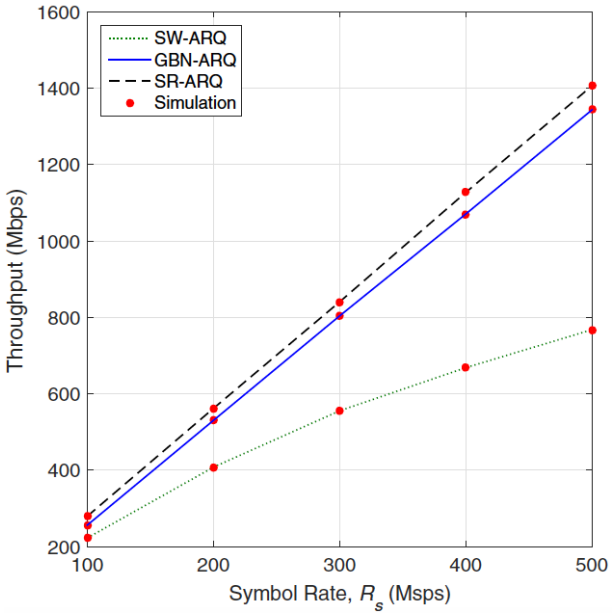
ARQ in FSO Terrestrial (2): Cross-layer Design

- *Second*, to promote using ARQ, most of previous works focused on the cross-layer design to further improve the FSO systems using ARQ

Paper	Link Layer	Physical Layer	Performance Metrics	Channels
[5] IEICE	SW-ARQ	Cooperative communications	Throughput, Delay, Energy Efficiency	Turbulence/ No pointing errors
[9] PJ	SW-ARQ	Adaptive rate transmissions	Spectral Efficiency, Outage Probability	Turbulence/ No pointing errors
[12] JOCN	GBN + SR-ARQ	Adaptive rate transmissions	Throughput, Delay, Frame Error Rate	Turbulence/ No pointing errors

All journals belong to CCL

[12]



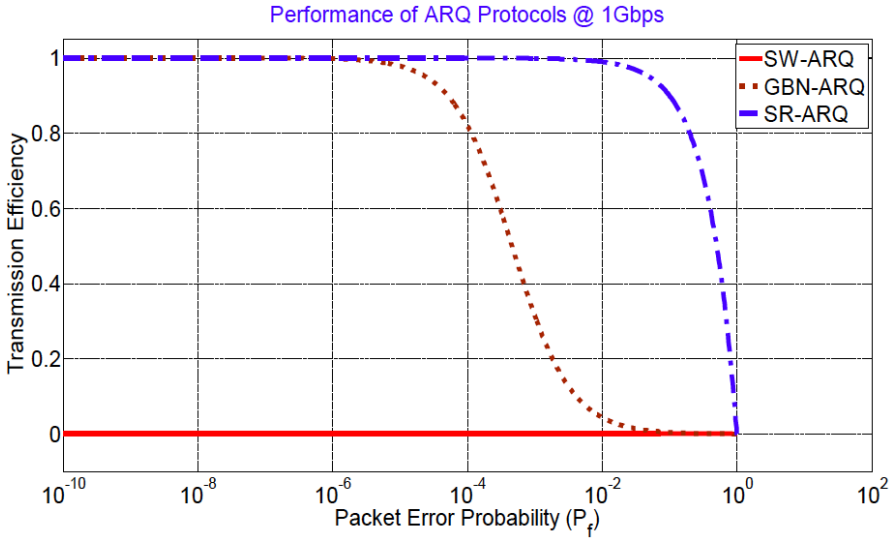
SW-ARQ may not suitable for high-speed FSO transmissions

ARQ in FSO Space Systems (1)

- Recent years, laser comm. is being considered for space systems, e.g., Satellite-assisted Internet of Vehicles and explore the universe.
- Several papers from ”well-known” companies (DLR and NASA) or Lab. (MIT) investigated the possibility of using ARQ for laser comm., mainly through the *simulations or experiments*.

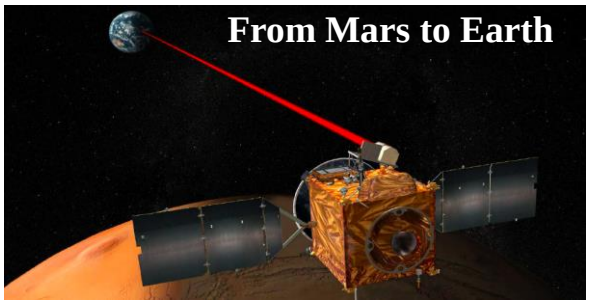
[7] and [8] investigated the throughput of ARQ for inter-HAP FSO systems (*DLR*)

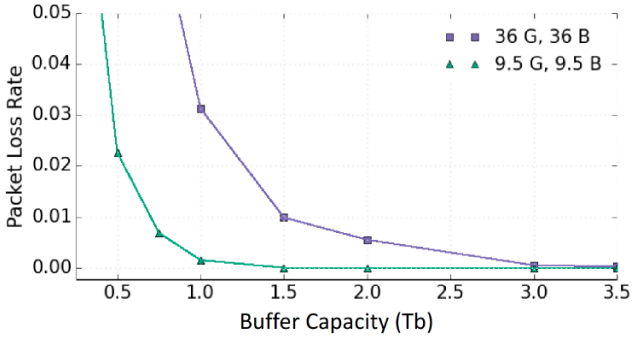
- Altitude: 17 km
- Distance: 516 km
- Pointing error + turbulence
- Simulations



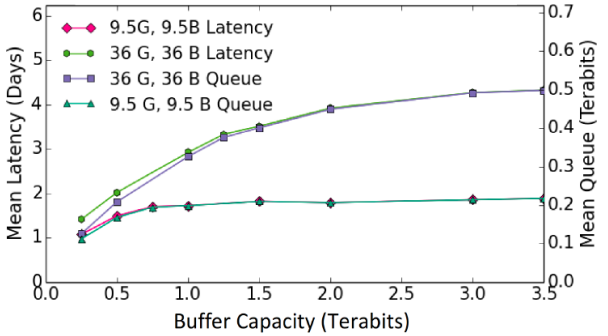
ARQ in FSO Space Systems (2)

[10] investigated the ARQ performance over Deep Space Optical links (*NASA*)





Mean duration of Good and Bad states are {9.5, 9.5} or {36, 36} hours

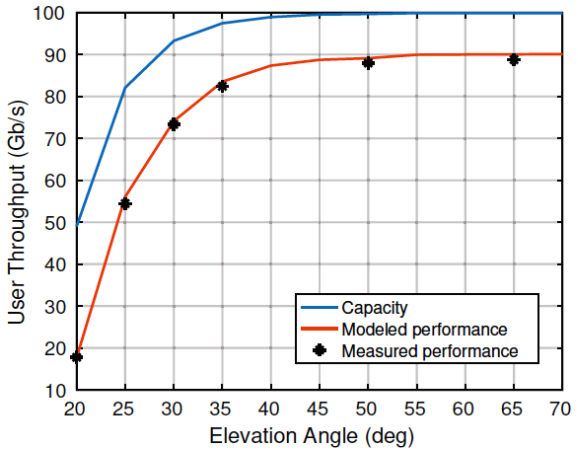


Packet latency with unbounded persistent ARQ

- NS3 and MC simulation, test for a Mars 2022 mission of NASA
- One-way light time: 22.4 min ~ max distance of Mars-Earth (401 million km)
- Link active: 8 hours/day, this will be changed day-by-day in actual systems (5.17 – 11 hours)
- Selective repeat ARQ is used

[11] Conducted a simple experiment to demonstrate the Satellite laser links using ARQ (*MIT*)

- Selective repeat ARQ is used
- LEO satellite to ground station (orbit altitude = 400 km)
- *Note*:
  + Unconstrained capacity = $(1-p)\times 100$ Gbps with p is the outage prob.
  + Modeled performance: including ARQ framing overhead (~10%) and delay

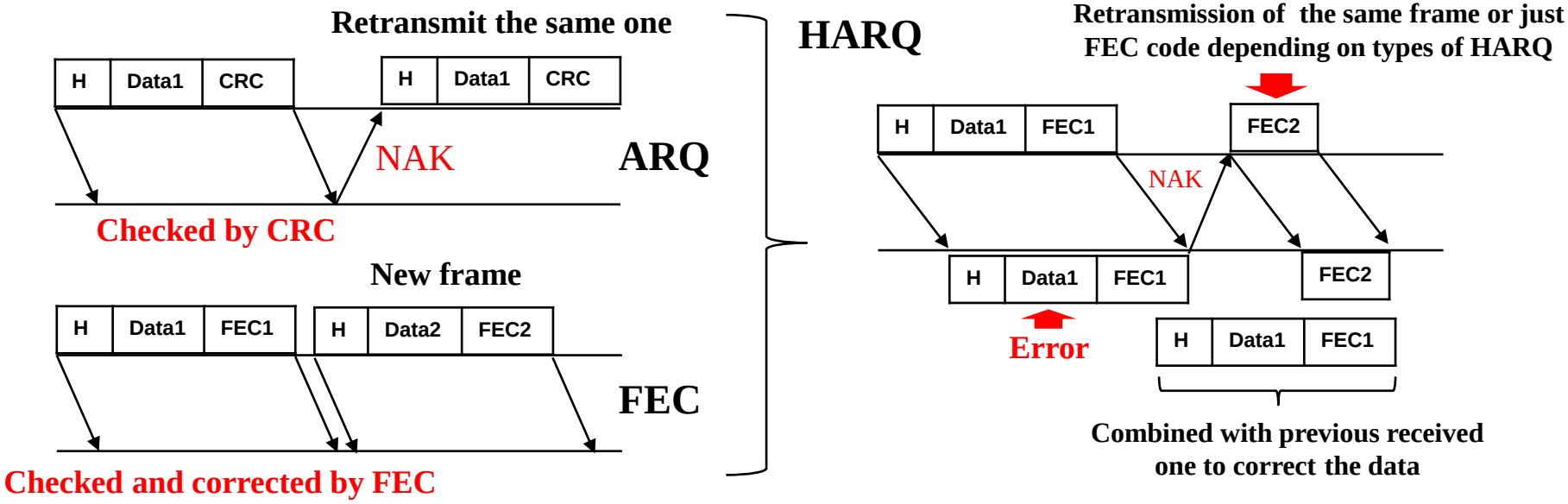


Part II: HARQ Aided FSO Communications

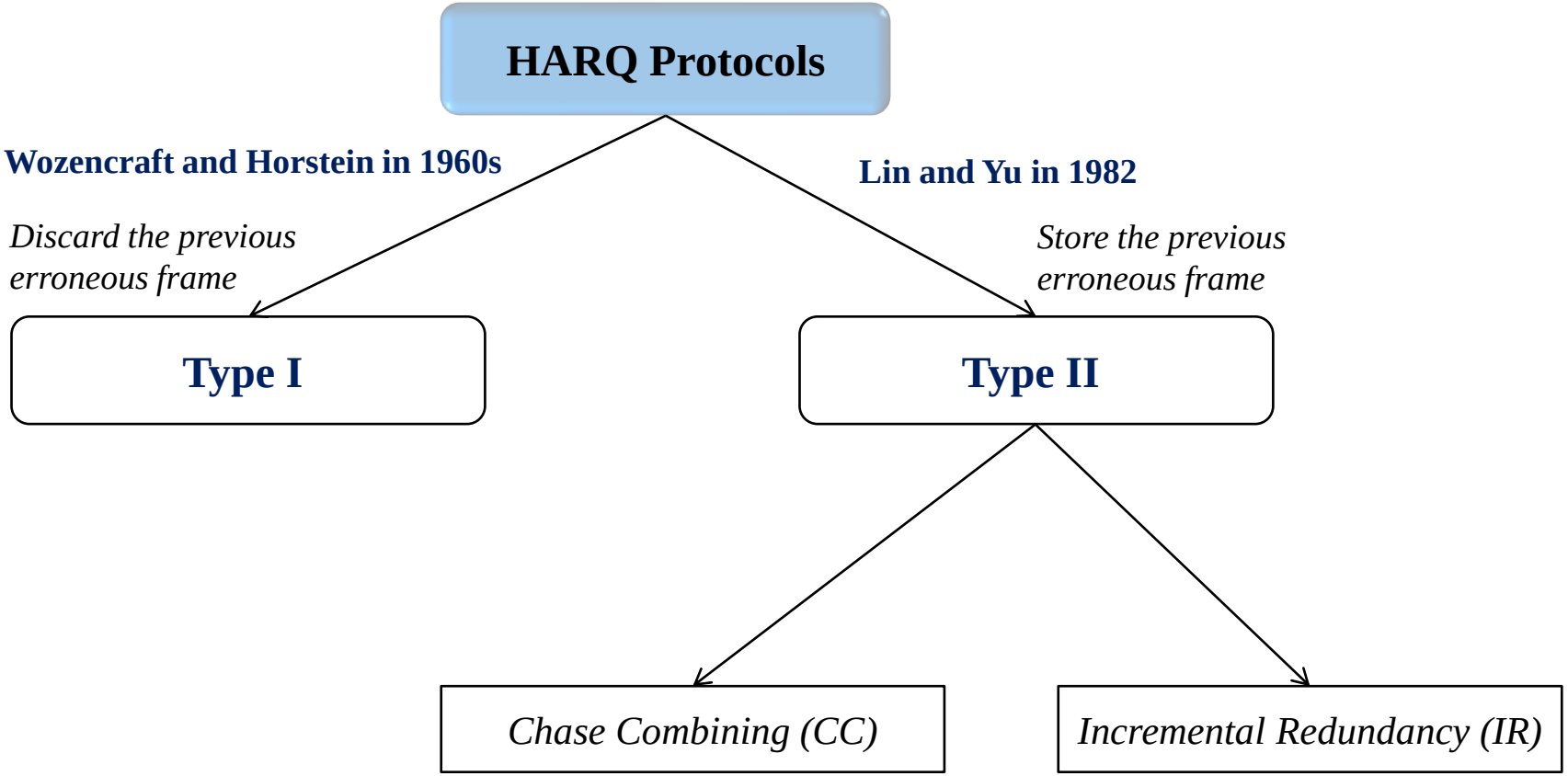
- ARQ protocols are able to work well in FSO systems, *however*
  - They may not be efficient in some scenarios
    - E.g., strong turbulence conditions, long-distance of satellite systems
  - The need of more robust error control protocols

→ HARQ is an enhanced version of ARQ used widely for wireless comm.

- **Definition**: HARQ is a combination of ARQ and FEC



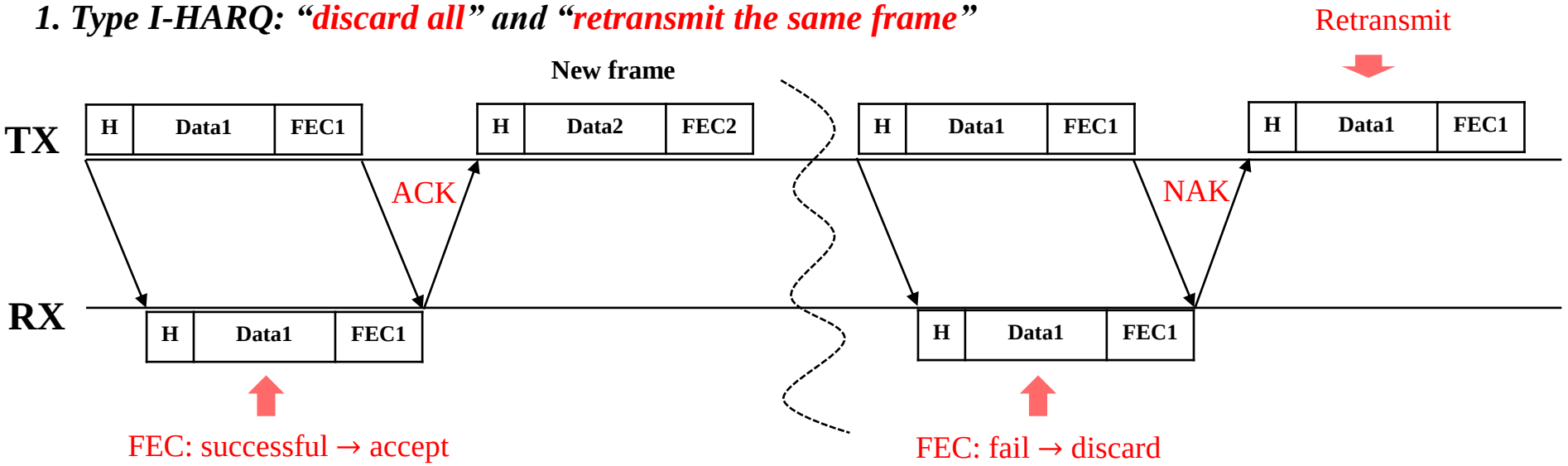
HARQ Protocol: Classification



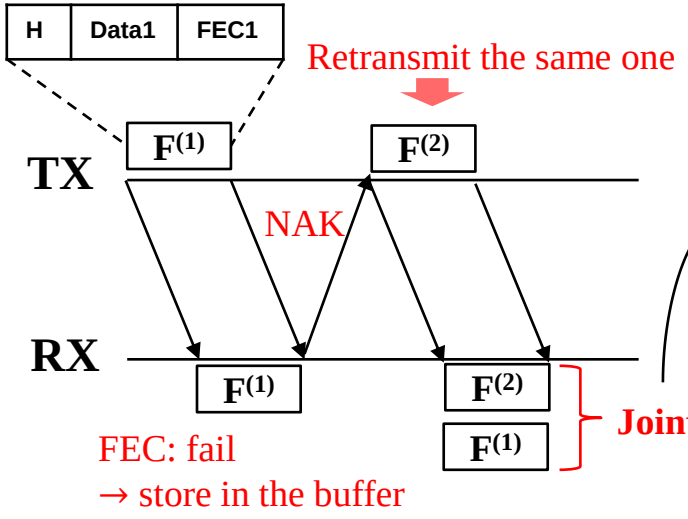
Type II-HARQ protocols are more popular than Type I

HARQ Protocols: How They Work? (1)

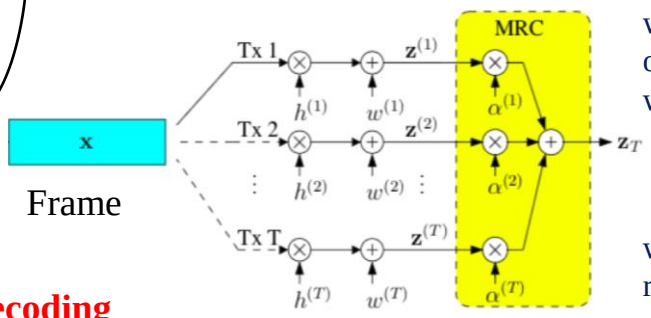
1. Type I-HARQ: "discard all" and "retransmit the same frame"



2. CC-HARQ: "store all" and "retransmit the same frame", then "combine with previous received ones"



How ??? → using Maximum ratio combining (MRC) techniques



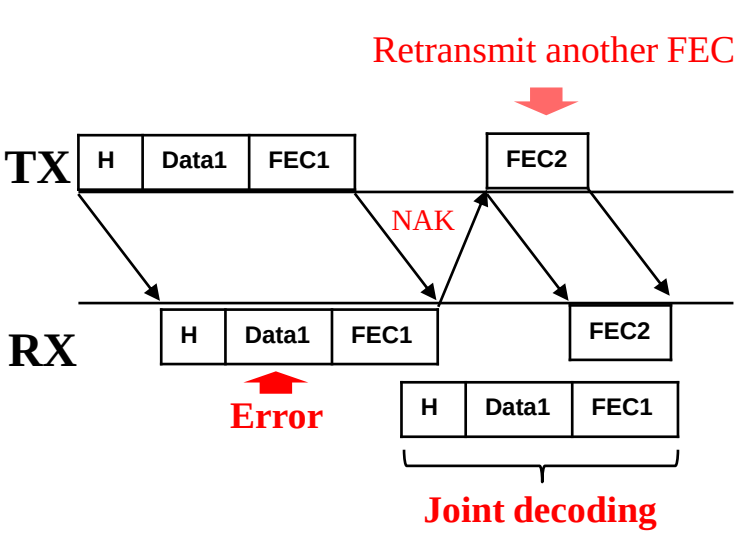
- The combined frame is obtained by weighting each frame by an estimate of its reliability before being summed with the other frames, i.e.,

$$z_T = \sum_{t=1}^{T} \alpha^{(t)} z^{(t)},$$

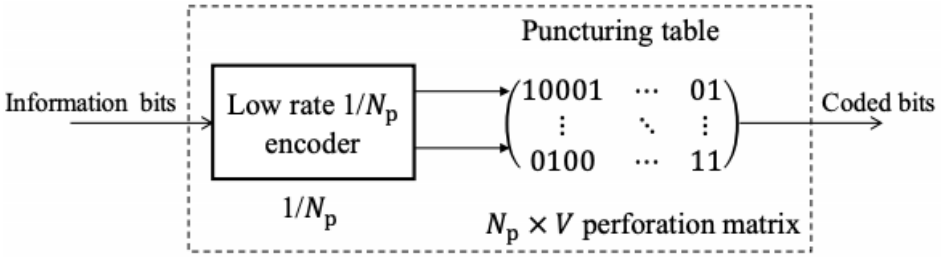
where $\alpha^{(t)}$ is the reliability of each received frame, which is given under maximum likelihood decoding.

HARQ Protocols: How They Work? (2)

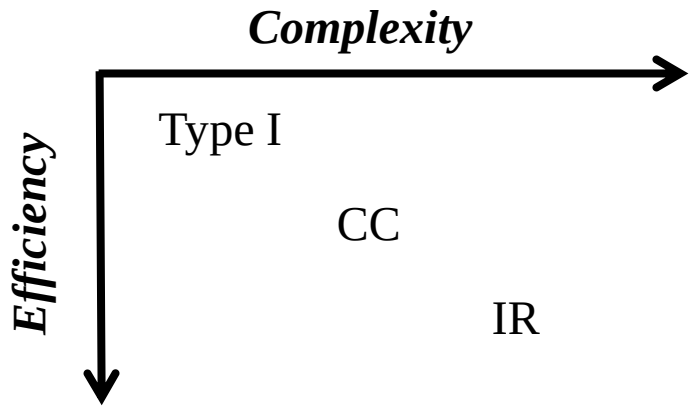
3. IR-HARQ: "store all" and "retransmit only FEC", then "combine with previous received ones"



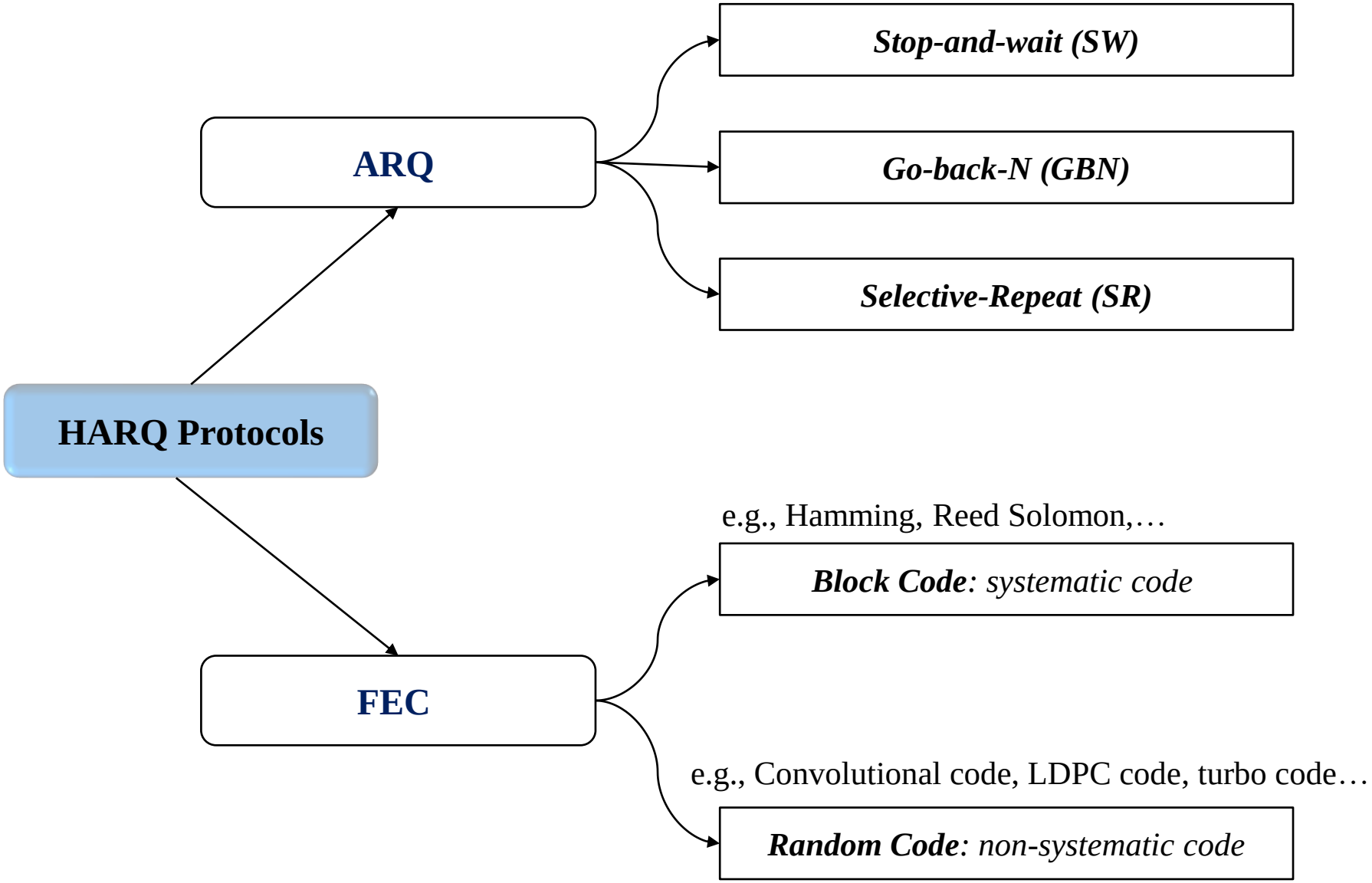
How ??? → using Puncturing techniques



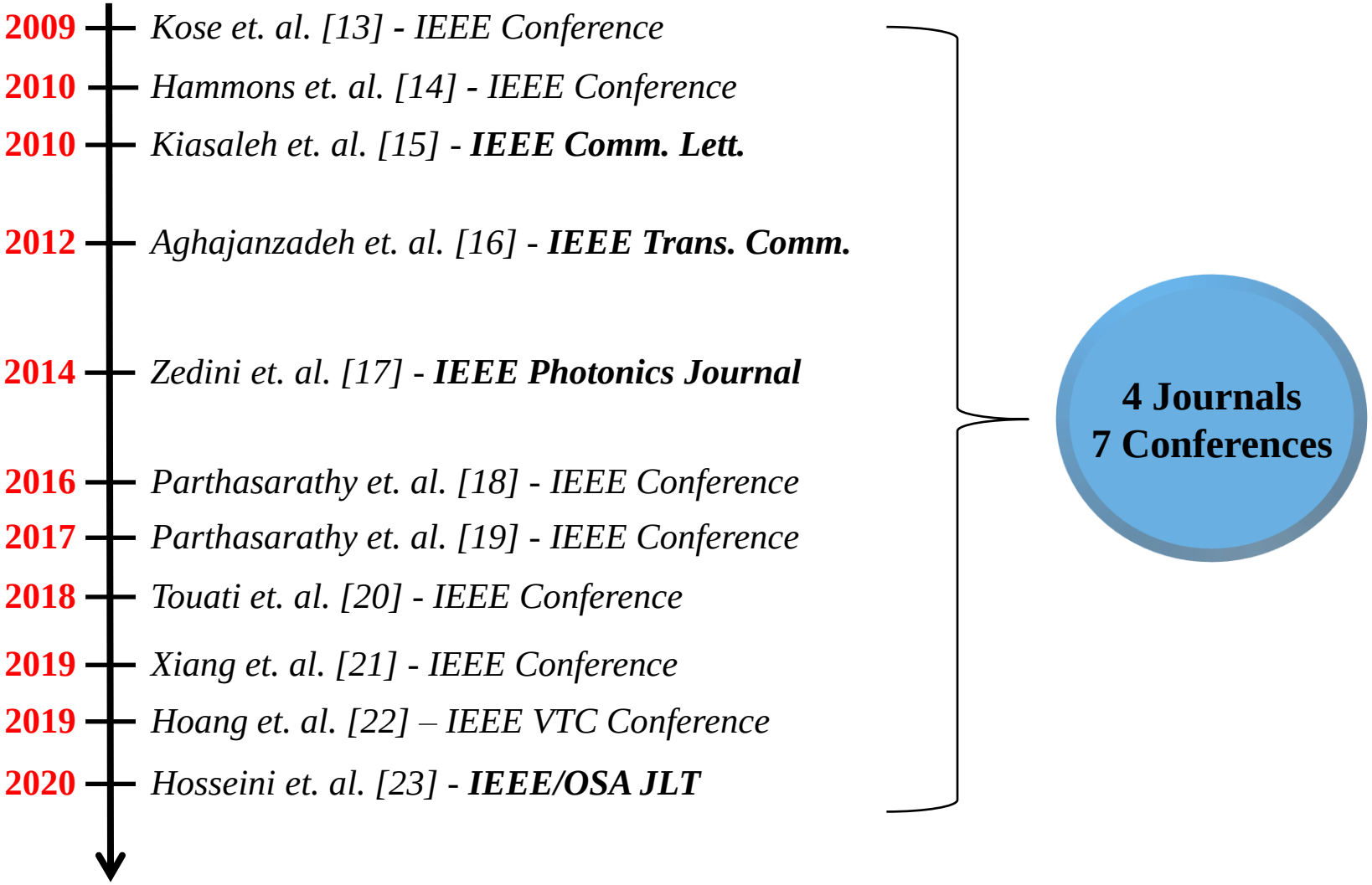
4. Comparison between protocols



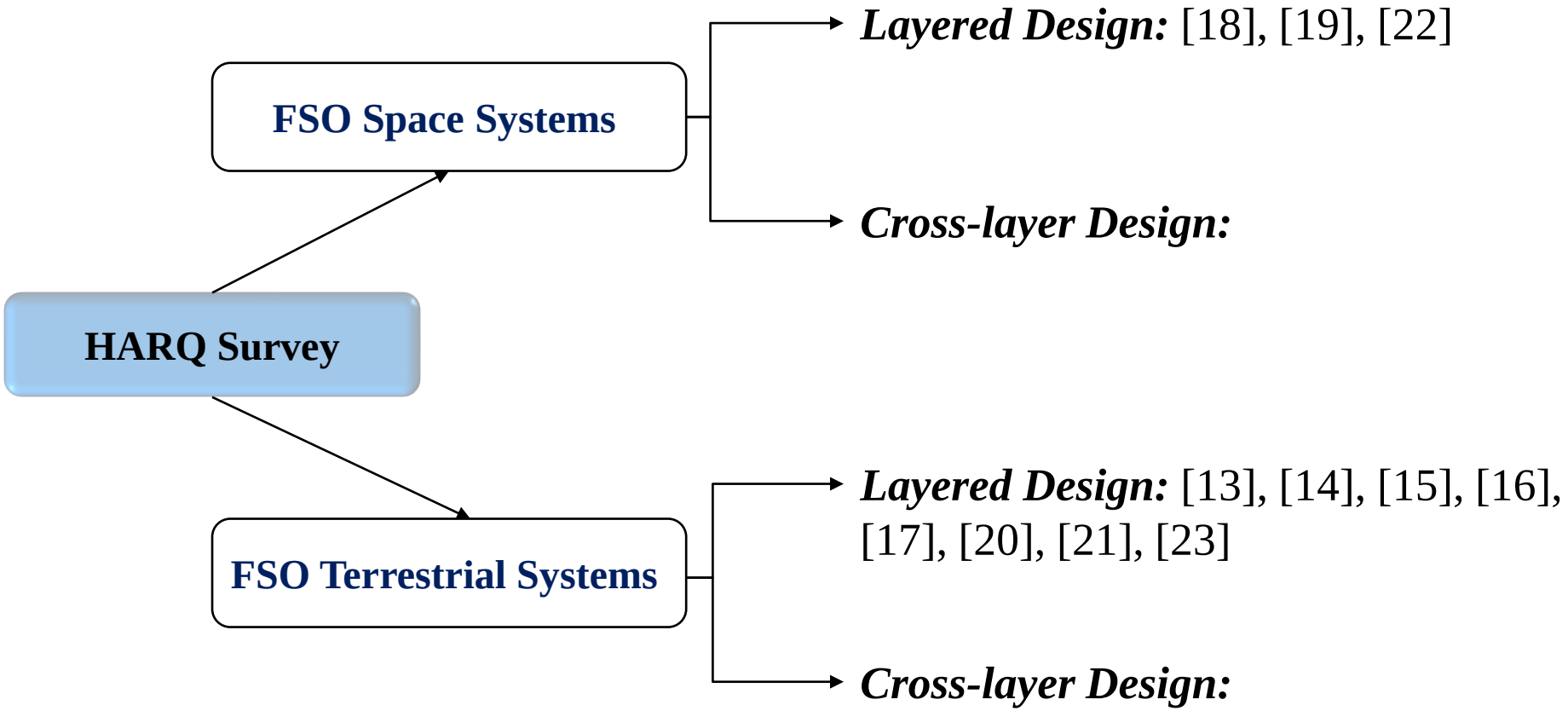
HARQ Protocols: How They Work? (3)



State-of-art of FSO Systems Using HARQ (1)

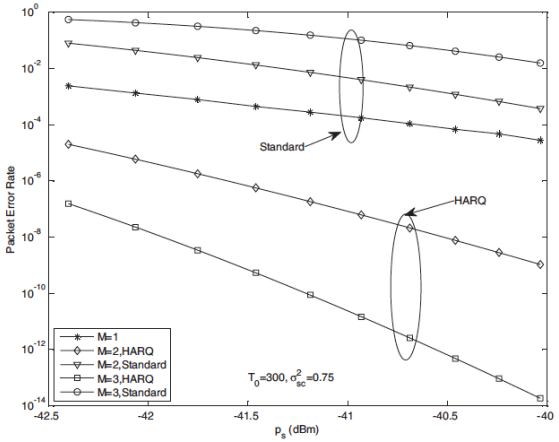


State-of-art of FSO Systems Using HARQ (2)



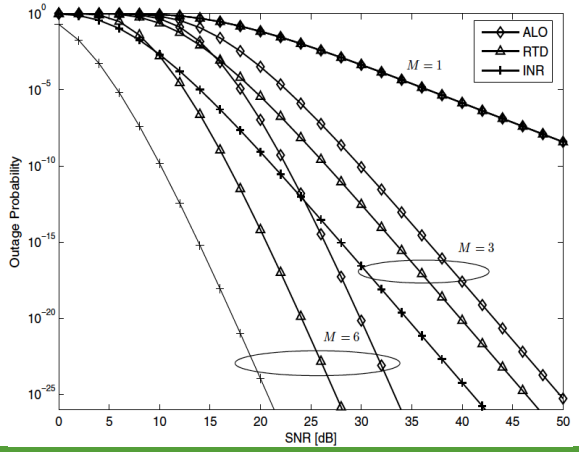
HARQ in FSO Terrestrial Systems (1)

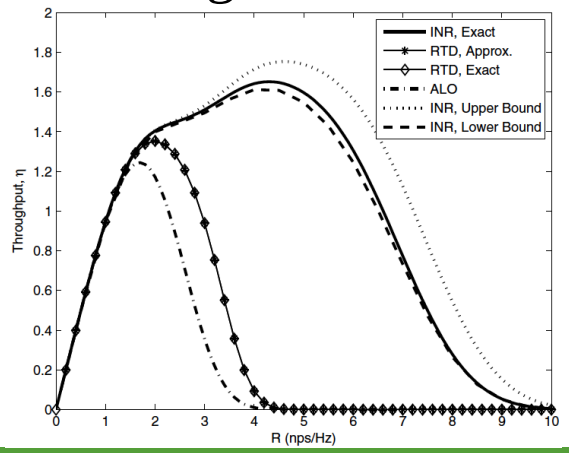
- *First*, [15] confirmed the effectiveness of using HARQ by comparing with "pure" ARQ in FSO terrestrial systems
  - CC-HARQ was investigated



- *Second*, [16] compared three types of HARQ and pointed out that IR-HARQ is the most efficient type over turbulence fading channels

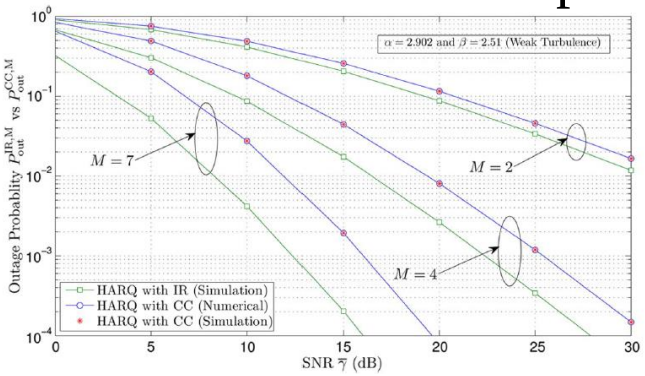
***NOTE:**
- ALO: Type I-HARQ
- RTD: CC-HARQ
- INR: IR-HARQ

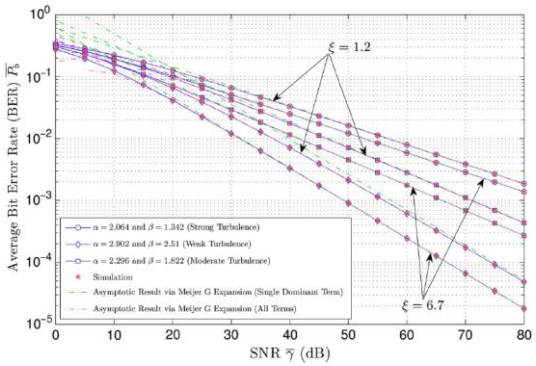




HARQ in FSO Terrestrial Systems (2)

- *Third*, [17] investigated the performance of CC and IR-HARQ under the combined effect of pointing errors and atmospheric turbulence.

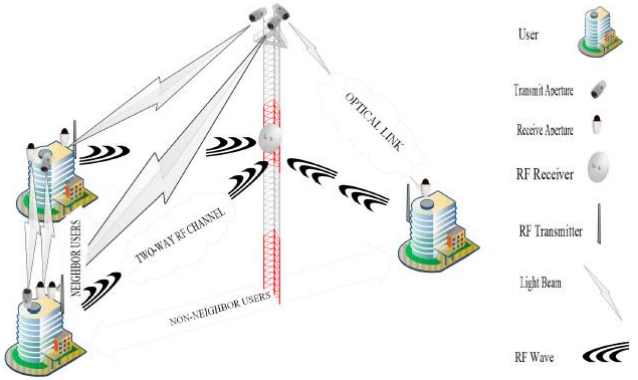




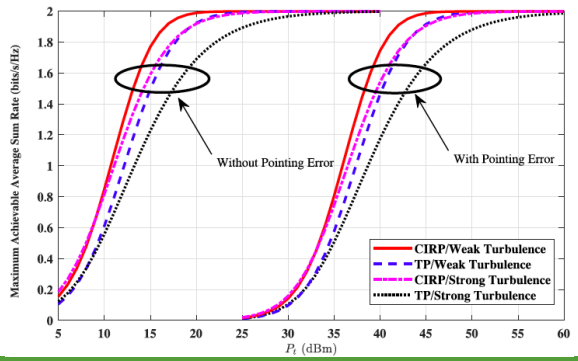
The average received SNR to achieve BER = 2×10^{-5} is 80 dB in weak turbulence and weak pointing error conditions.

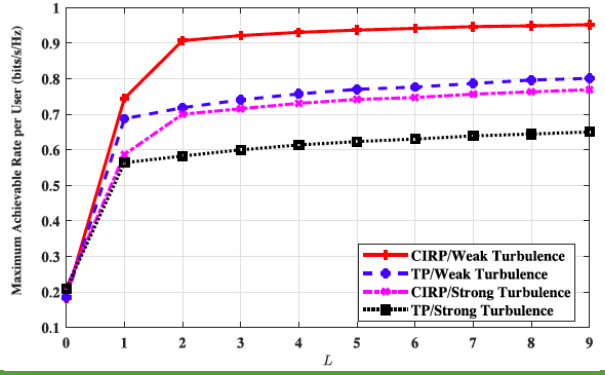
???????

- *Fourth*, [23] proposed a new HARQ protocol for broadcasting systems



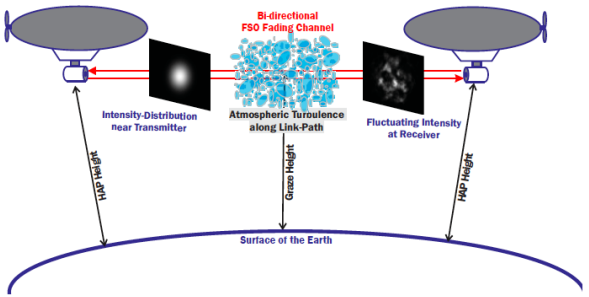
Upon receiving a NAK from a given user, instead of relying on the central node, a user who successfully decoded the original data packet and whose distance from the NACK issuing user is smaller than that of the central node, is invited to retransmit this packet.

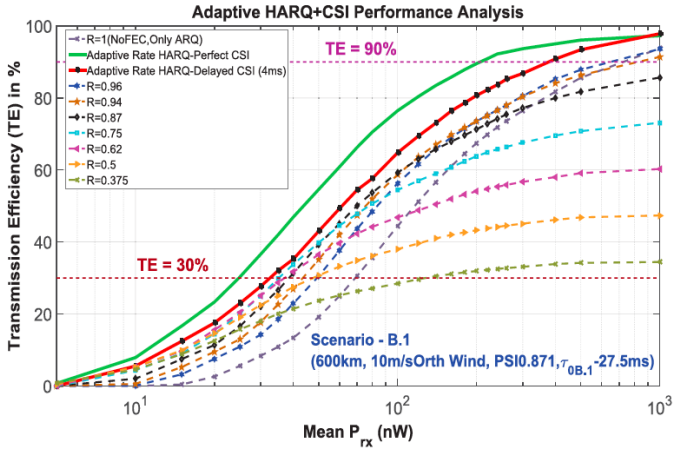




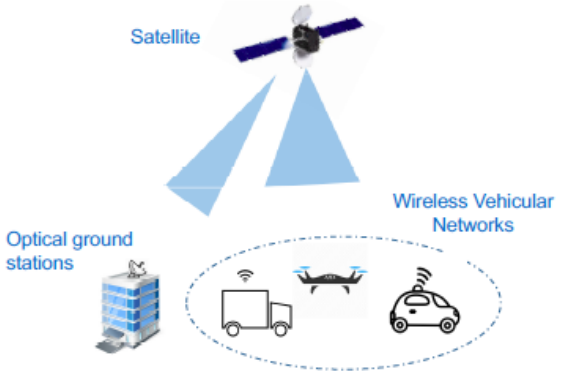
HARQ in FSO Space Systems

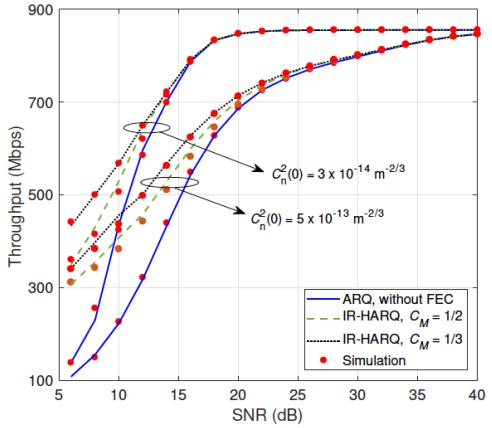
- [18] and [19] (from DLR) presented simulative performance analysis of Type I HARQ with adaptive-code rate Reed-Solomon code and selective repeat ARQ for inter-HAPs based FSO transmissions.





- [22] investigated the design and performance of IR-HARQ for satellite systems





Remaining Issues and Some Future Directions

- Remaining Issues
  - SW-ARQ was used for terrestrial FSO systems → not efficient for high-speed FSO communications
  - No cross-layer design is investigated for both terrestrial and space systems
- Some Future Directions
  - HARQ aided Cooperative Communications
    - For network of Vehicles using FSO communications
  - HARQ aided Non orthogonal multiple access (NOMA)
    - Satellite with wide beam footprint can assist for multiple access of vehicles e.g., multiple UAVs and self-driving cars
  - The investigation of adaptive-rate HARQ with imperfect Channel State Information (CSI)
    - Especially useful for Satellite Communications where the CSI feedback may be outdated due to the long delay.

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Thank You For Your Listening!